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Comprehensive Evaluation of Sustainable Treatment Technology of Oily Sludge Based on AHP-FCE

Jiwei Wu [1], Shifan Zhang [2], Jian Li [3], Jiankun Liu [4], Haocheng Sun [4], Zixian Jia [4], Ye Xia [5], Jie Liu [6], Dongliang Pan [6], Jianqiang Sun [6], Xianzhong Yi [3] and Liang Ma [1,*]

[1] College of Carbon Neutrality Future Technology, Sichuan University, Chengdu 610065, China; wu_jiwei@scu.edu.cn (J.W.)
[2] School of Future Technology, China University of Geosciences, Wuhan 430074, China; zhangshifan0314@163.com (S.Z.)
[3] School of Mechanical Engineering, Yangtze University, Jingzhou 434023, China; lijian010225@163.com (J.L.); 124822351@qq.com (X.Y.)
[4] Dalian Petrochemical Research Institute, Dalian 116045, China; liujiankun.dshy@sinopec.com (J.L.); sunhaohceng.fshy@sinopec.com (H.S.); jiazixian.fshy@sinopec.com (Z.J.)
[5] Sinopec Shengli Petroleum Engineering Co., Ltd., Dongying 257000, China; xiaye34@163.com (Y.X.)
[6] College of Mechanical and Electrical Engineering, Southwest Petroleum University, Chengdu 610500, China; 1638340450@qq.com (J.L.); 1374583844@qq.com (D.P.); jianqiangsun@swpu.edu.cn (J.S.)
* Corresponding author. E-mail: maliang@scu.edu.cn (L.M.)

Received: 4 August 2023; Accepted: 18 September 2023; Available online: 7 October 2023

ABSTRACT: Oil is an unsustainable energy since it is non-renewable. However, oil may not be completely replaced in a short time, so the environmental problems caused by the oil development still require our attention. The oily sludge is a kind of hazardous waste produced during the oil development. To reduce the environmental impact caused by oily sludge, low-carbon and sustainable treatment technologies need to be selected. The incineration, chemical extraction and thermal desorption are common technologies for treatment of oily sludge. We calculated the carbon emissions of these technologies. Then the index evaluation system of oily sludge treatment technology was established with the environmental, economic, social, and technical factors. And the weight of evaluation index was determined by the analytic hierarchy process (AHP). Through the investigation of industry experts, we evaluated the treatment technologies by the fuzzy comprehensive evaluation method (FCE). The results showed that the carbon emissions of incineration are 42.70 t CO_2-eq/t which is the highest. Meanwhile, it is 4.80 t CO_2-eq/t and 0.10 t CO_2-eq/t for chemical extraction and thermal desorption, respectively. The comprehensive scores of incineration, chemical extraction and thermal desorption were 4.59, 5.16 and 4.95, respectively. Therefore, the chemical extraction technology is an optimal treatment technology for oily sludge with the relatively low carbon emission and the highest comprehensive technical score. At the same time, the thermal desorption technology has strong application potential with the lowest carbon emissions. This result provides a reference for achieving clean and sustainable energy development processes.

Keywords: Oily sludge; Clean technology; Carbon emissions; Analytic hierarchy process; Fuzzy comprehensive evaluation

1. Introduction

In the process of oil exploitation and processing, a large amount of waste oily sludge is produced. These sludges are discharged directly into the environment without treatment, which will seriously endanger the safety of the environment and human health [1–3]. In order to reduce the harm of oily sludge, the commonly used treatment technologies are: incineration, chemical extraction and thermal desorption [4]. Because these treatment technologies have their own advantages and disadvantages in terms of treatment effect and operation difficulty, how to scientifically and reasonably evaluate these technologies and select the most suitable oily sludge treatment technology for the oil industry has become an urgent problem to be solved [5].

At present, the commonly used technical evaluation methods for oily sludge at home and abroad mainly include: analytic hierarchy process [6–10], fuzzy comprehensive evaluation method [11,12], grey correlation analysis method [13,14], Delphi method [15] and data envelopment analysis method [16]. In the process of system evaluation, the comments used are usually ambiguous, and the fuzzy comprehensive evaluation method (FCE) is most suitable. However, the weight of fuzzy evaluation is given by experts based on experience, which is inevitably subjective [17]. The analytic hierarchy process (AHP) is a quantitative evaluation of the

https://doi.org/10.35534/ces.2023.10007

qualitative indicators in the evaluation system, which can minimize the drawbacks caused by personal subjective assumptions and make the evaluation results more realistic [18,19]. By combining AHP and FCE [20], a comprehensive quantitative evaluation of multiple factors in the evaluation system can be carried out. The AHP-FCE method has been applied in many fields, including the evaluation of water pollution control technology in zinc smelting industry [18], the evaluation of cleaner production technology in pharmaceutical industry [21], the selection of sewage sludge heat treatment process [22], the impact of oil projects on the environment [23], the evaluation of the best technology of cold rolled coil manufacturing process [24] and the evaluation of heavy metal pollution prevention and control technology [21]. The above cases have achieved good results by using this method.

With the continuous promotion of the national practice of green low-carbon action, the research on carbon emissions of various production technologies has gradually become a trend. At present, there are few studies on the application of carbon emission evaluation to oily sludge treatment technology. Moreover, the evaluation of oily sludge treatment technology is a complex multi-objective decision-making problem [14], which involves many factors, so it needs to be considered from multiple levels.

This paper will evaluate the oily sludge treatment technology from four aspects of environment, economy, society and technology. Since China is the world's largest carbon emitter, and the production of industrial technology is closely related to carbon emissions, this paper first considers the impact of processing technology on the environment, and uses the emission factor method to calculate the carbon emissions of processing technology. Secondly, considering the impact of these four aspects, the appropriate processing technology is selected through the comprehensive score of AHP-FCE. The research content provides theoretical support for oilfield enterprises to choose oily sludge treatment technology according to local conditions.

2. Research Methods

2.1. Carbon Emissions Accounting Method

In order to reduce the impact of industrial technology on the environment, the carbon emissions of various technologies have strict requirements. Carbon emissions accounting is the premise of effective carbon reduction work. It can directly quantify the data of carbon emissions. At present, the accounting methods of carbon emissions mainly include emission factor method, mass balance method and measurement method. Because the emission factor method has the advantages of wide application range and can calculate the carbon emissions of specific regions, this paper chooses the emission factor method, and the calculation formula is as follows [25].

The power consumption is as formula (1).

$$E_{\mathrm{e,CO_2}} = \sum K_{\mathrm{e}i} \times EF_{\mathrm{e}i} \tag{1}$$

In the formula above, $E_{\mathrm{e,CO_2}}$ is the CO_2 emissions from electricity consumption, kg; K_{ei} is the power consumption, KW·h; EF_{ei} is the carbon emission factor for electricity, kg CO_2/KW·h.

The natural gas consumption is as formula (2).

$$E_{\mathrm{h,CO_2}} = \sum K_{\mathrm{h}i} \times EF_{\mathrm{h}i} \tag{2}$$

In the formula above, $E_{\mathrm{h,CO_2}}$ is the CO_2 emissions from natural gas consumption, kg; K_{hi} is the natural gas consumption, m^3; EF_{hi} is the carbon emission factor for natural gas, kg CO_2/m^3.

The chemical consumption is as formula (3)

$$E_{\mathrm{m,CO_2}} = \sum K_{\mathrm{m}i} \times EF_{\mathrm{m}i} \tag{3}$$

In the formula above, $E_{\mathrm{m,CO_2}}$ is the CO_2 emissions from the use of chemical, kg; K_{mi} is the consumption of chemical, kg; EF_{mi} is the carbon emission factors for chemical, kg CO_2/kg.

In the above calculation formulas, the carbon emission coefficient of electricity is determined according to the document issued by the Ministry of Ecology and Environment "Notice on Doing a Good Job in the Management of Greenhouse Gas Emission Reports of Power Generation Industry Enterprises in 2023–2025". The average emission factor of the national power grid in 2022 is 0.5703 t CO_2/MW·h [26]; the carbon emissions of energy and materials are determined according to various CO_2 emission factors included in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [27]. It can be seen that the carbon emission factor of natural gas is 2.66 kg CO_2/m^3, the carbon emission factor of fuel coal is 2.53 kg CO_2/kg, the production emission factor of diesel oil is 2.73 kg CO_2/L, and the carbon emission factor of extractant is 1.60 kg CO_2/L.

2.2. AHP-FCE Analysis Method

The AHP-FCE method is a more comprehensive evaluation system at present. The evaluation model consists of two parts, which echo each other. The evaluation process of sustainable treatment technology for oily sludge is shown in Figure 1.

2.2.1. Establishment of Oily Sludge Technology Evaluation System

Based on the characteristics of oily sludge, such as great harm, high treatment difficulty and strong treatment timeliness [28], the AHP-FCE model for the evaluation of oily sludge treatment technology is established. The model includes 4 primary indicators and 19 secondary indicators, as shown in Figure 1.

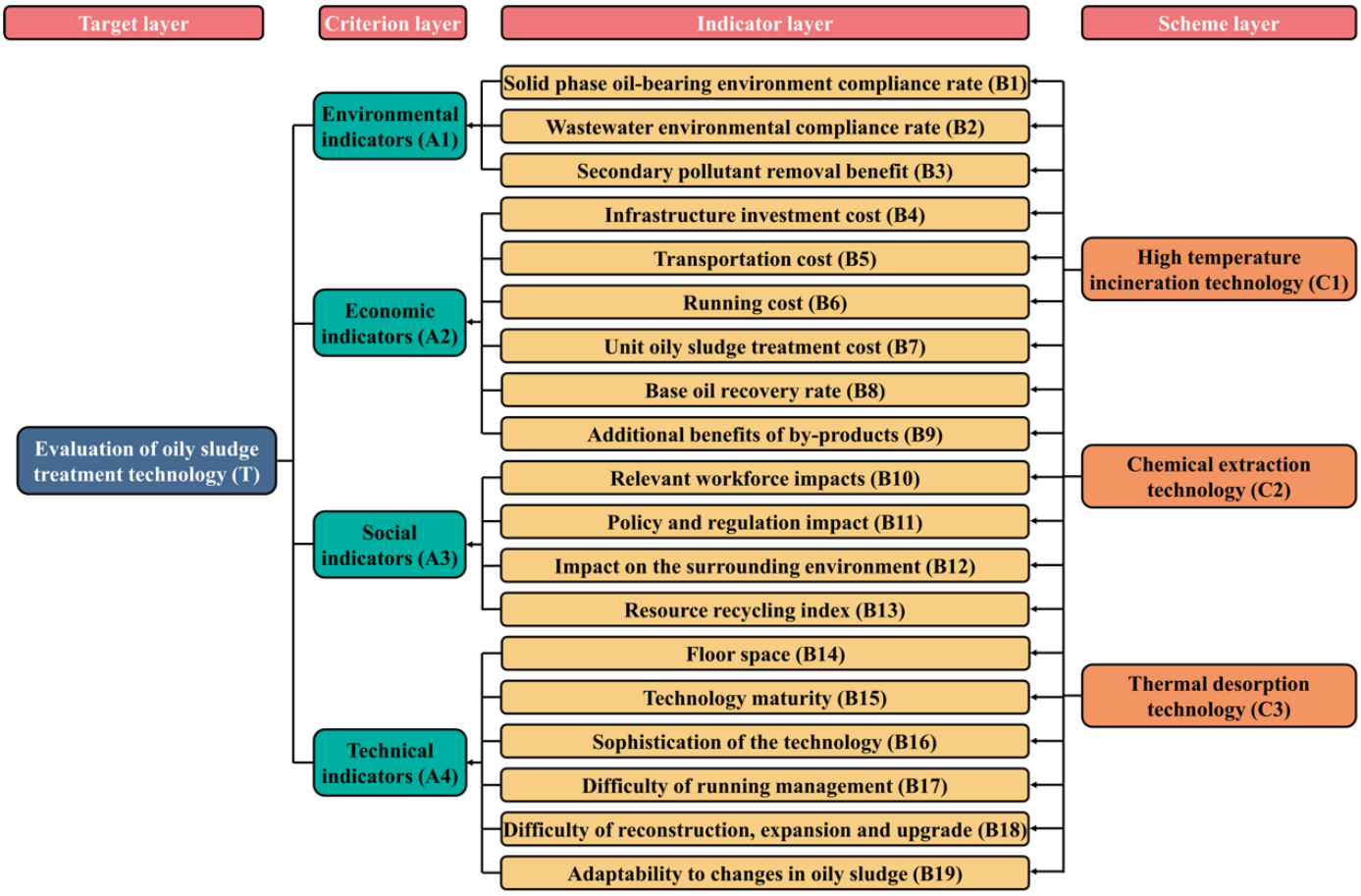

Figure 1. Evaluation system of the best applicable technology for oily sludge treatment in Chinese Shengli Oilfield.

2.2.2. Calculation of weights using AHP

To determine the importance of each element to the previous level, this study cites a scaling method of 1–9 and its reciprocal. The meaning of the judgment scale is shown in Table 1, and the indicators are assessed by the use of expert survey. The judgment matrix W of the importance relationship between each evaluation indicator is shown in formula (4) [29].

$$W = (a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (4)$$

Based on the obtained judgment matrix W, the square root method is used to determine the weights of the evaluation indicators at all levels, as shown in formula (5)

$$M_i = \frac{\sqrt[n]{\prod_{j=1}^{n} a_{ij}}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j=1}^{n} a_{ij}}} \quad (5)$$

Therefore, $N_i = (M_1, M_2, \cdots, M_n)^T$ is the eigenvector of matrix W.

The maximum eigenvalue can be calculated by equation (6).

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(WN)_i}{nM_i} \tag{6}$$

In the formula above, $(WN)_i$ is the ith component of matrix WN.

We calculate the consistency ratio of judgment matrix C_R using formula (7). If $C_R < 0.1$, then the judgment matrix is considered to pass the consistency test.

$$C_R = \frac{C_I}{R_I} = \frac{\lambda_{\max} - n}{(n-1)R_I} \tag{7}$$

In the formula above, C_I is the matrix consistency indicator, and R_I is the average random consistency indicator.

Through the investigation of solid waste managers, on-site drilling engineers and experts engaged in the research of oily solid waste in scientific research units of Shell, Chinese National Petroleum Corp and Sino Petroleum Corp, a total of 10 questionnaires was obtained. Through the evaluation of the relative importance of the evaluation indexes of the processing technology by various relevant workers, the judgment matrix of the criterion layer and each index layer was obtained, and the weight was calculated by the square root method (helped by Yaahp V10.5 software).

After calculation, the judgment matrix C_R value of the criterion layer and each indicator layer was less than 0.1, and hence each weight value can be applied. After obtaining the weights of each criterion layer and indicator layer, based on the total ranking principle of AHP, the comprehensive weight value of each indicator to the total target "best technology" was obtained.

Table 1. Judgment matrix scale and its meaning.

Scaling	Definition
1	The i factor is as important as the j factor
3	The i factor is slightly more important than the j factor
5	The i factor is more important than the j factor
7	The i factor is much more important than the j factor
9	The i factor is absolutely more important than the j factor
Reciprocal	If the i and j factors are compared, and the judgment value is a_{ij}, then $a_{ji} = 1/a_{ij}$
2, 4, 6, 8	Importance levels between 1,3,5,7,9

2.2.3. Construction of the Fuzzy Comprehensive Evaluation

(1) Construction of the value set and index membership

By constructing a value set $V = (V_1, V_2, V_3, V_4, V_5, V_6, V_7)$ = (Excellent, Great, Good, Medium, Ordinary, Bad, Poor). After we considered the evaluation index system of oily sludge treatment technology comprehensively, we determined the evaluation grade standard through on-site research and sampling, experiments on the physical and chemical properties of oily sludge, and expert discussion (Table 2). Then, through expert judgment and statistical analysis of the results, the membership degree matrix R_i was obtained.

(2) Multi-level fuzzy comprehensive evaluation

According to the hierarchical structure model, a two-level fuzzy comprehensive evaluation was adopted. First, according to formula (8), we constructed a fuzzy membership matrix R_i and weight matrix W_i of the indicator layer B contained in the criterion layer A_i, and obtained the membership degrees of different evaluation levels corresponding to each index in criterion layer A through first-level fuzzy synthesis operation. According to formula (9), we obtained the second-level fuzzy comprehensive value set [30].

$$A_i = W_i \times R_i \tag{8}$$

$$T = W \times R \tag{9}$$

(3) Comprehensive evaluation score

The performance description of the index value set "excellent, very good, better, medium, general, poor and poor" is given 7 points, 6 points, 5 points, 4 points, 3 points, 2 points and 1 point respectively. Table 3 shows three oily sludge treatment technologies.

The final fuzzy comprehensive evaluation value set of the oily sludge treatment technology was multiplied by the corresponding weights of the indicators to obtain the final comprehensive evaluation score.

Table 2. Evaluation indicators.

Criterion	Indicator	Description
Environmental indicators (A1)	Solid-phase oil-bearing environment compliance rate (B1)	Whether the treated sludge meets standard of the oil content ≤0.3% [31]
	Wastewater environmental compliance rate (B2)	Whether the discharge of petroleum water pollutants meets the "Discharge Standard of Pollutants for Petroleum Refining Industry" [32]
	Secondary pollutant removal benefit (B3)	Including toxic and harmful gases, dust, heavy metals, organic highly toxic pollutants, chemical reaction products and other secondary pollutants
Economic indicators (A2)	Infrastructure investment cost (B4)	The overall construction cost of the treatment station or the purchase cost of the complete set of equipment
	Transportation cost (B5)	Transportation of sludge, crude oil, solids, water, etc.
	Operating cost (B6)	Expenses for daily operation and maintenance of processing station or complete set of equipment
	Unit sludge treatment cost (B7)	Energy consumption per ton of sludge treated
	Crude oil recovery rate (B8)	Whether the crude oil is recovered, whether the recovered crude oil meets the requirements for secondary slurry preparation, and the resource utilization rate of the recovered crude oil
	Additional benefits of by-products (B9)	Resource benefits including crude oil, heavy metal, water and other by-products
Social indicators (A3)	Workforce impacts (B10)	The impact of noise, dust, volatile matter toxicity and other operating environments on personnel health; labor intensity
	Policy and regulation impact (B11)	Whether it can obtain processing qualifications and whether it meets the requirements of local laws and regulations
	Impact on the surrounding environment (B12)	The impact of all gas, liquid and solid generated during operation on the surrounding ecology and residents
	Resource recycling index (B13)	Total resource recovery benefit of all gas phase, liquid phase and solid phase
Technical indicators (A4)	Floor space (B14)	Floor space occupied by the processing station or a complete set of equipment
	Technology maturity (B15)	Technical stability; whether there is pre-industrial application, and whether the application effect is good
	Technology complexity (B16)	The complexity of technical process, equipment structure, etc.
	Difficulty of operation and management (B17)	Difficulty of equipment operation, management and operation cooperation
	Difficulty of rebuilding, expanding and upgrading (B18)	Whether it can be expanded and upgraded; the cost and technical difficulty of expansion and upgrading
	Adaptability to sludge changes (B19)	Whether the sludge with different physical parameters (oil content, solid particle size, etc.) can be stably treated

Table 3. The score membership normalized date of the three technical evaluation indexes.

Evaluating indicator		Membership						
		Incineration Technology/Chemical Extraction Technology/Thermal Desorption Technology						
		Excellent 7	Great 6	Good 5	Medium 4	Ordinary 3	Bad 2	Poor 1
A1	Solid-phase oil-bearing environment compliance rate (B1)	0.3/0.2/0.4	0.5/0.3/0.3	0.1/0.3/0.3	0.1/0.0/0.0	0.0/0.2/0.0	0.0/0.0/0.0	0.0/0.0/0.0
	Wastewater environmental compliance rate (B2)	0.0/0.0/0.0	0.0/0.2/0.0	0.3/0.3/0.3	0.3/0.4/0.3	0.3/0.0/0.2	0.1/0.1/0.2	0.0/0.0/0.0
	Secondary pollutant removal benefit (B3)	0.1/0.1/0.0	0.0/0.2/0.0	0.1/0.5/0.2	0.1/0.2/0.5	0.3/0.0/0.3	0.2/0.0/0.0	0.2/0.0/0.0
A2	Infrastructure investment cost (B4)	0.0/0.0/0.0	0.1/0.0/0.0	0.2/0.3/0.2	0.3/0.3/0.3	0.0/0.4/0.4	0.2/0.0/0.1	0.2/0.0/0.0
	Transportation cost (B5)	0.0/0.1/0.0	0.0/0.2/0.1	0.2/0.2/0.3	0.2/0.3/0.4	0.3/0.2/0.2	0.1/0.0/0.0	0.2/0.0/0.0
	Operating cost (B6)	0.0/0.0/0.0	0.0/0.1/0.2	0.3/0.3/0.2	0.2/0.3/0.4	0.2/0.1/0.2	0.3/0.0/0.0	0.0/0.2/0.0
	Unit sludge treatment cost (B7)	0.1/0.2/0.0	0.0/0.0/0.0	0.1/0.3/0.2	0.0/0.2/0.4	0.3/0.2/0.3	0.4/0.0/0.1	0.1/0.1/0.0
	Crude oil recovery rate (B8)	0.0/0.3/0.0	0.0/0.2/0.0	0.0/0.4/0.0	0.0/0.1/0.5	0.1/0.0/0.3	0.4/0.0/02	0.5/0.0/0.0
	Additional benefits of by-products (B9)	0.0/0.1/0.0	0.0/0.3/0.2	0.1/0.4/0.3	0.0/0.2/0.0	0.0/0.0/0.5	0.4/0.0/0.0	0.5/0.0/0.0
A3	Workforce impacts (B10)	0.0/0.0/0.1	0.1/0.3/0.2	0.0/0.5/0.0	0.1/0.0/0.3	0.5/0.2/0.4	0.3/0.0/0.0	0.0/0.0/0.0
	Policy and Regulation Impact (B11)	0.0/0.2/0.0	0.2/0.0/0.2	0.2/0.5/0.3	0.4/0.3/0.4	0.2/0.0/0.1	0.0/0.0/0.0	0.0/0.0/0.0
	Impact on the surrounding environment (B12)	0.0/0.3/0.0	0.0/0.3/0.0	0.1/0.0/0.2	0.1/0.4/0.4	0.5/0.0/0.0	0.3/0.0/0.3	0.0/0.0/0.2
	Resource recycling indicator (B13)	0.0/0.0/0.0	0.0/0.4/0.2	0.0/0.4/0.3	0.1/0.2/0.2	0.1/0.0/0.0	0.3/0.0/0.1	0.5/0.0/0.2
A4	Floor space (B14)	0.0/0.2/0.0	0.1/0.3/0.3	0.0/0.1/0.2	0.3/0.4/0.2	0.5/0.0/0.0	0.1/0.0/0.2	0.0/0.0/0.1
	Technology maturity (B15)	0.1/0.0/0.2	0.5/0.4/0.4	0.2/0.3/0.0	0.1/0.3/0.4	0.1/0.0/0.0	0.0/0.0/0.0	0.0/0.0/0.0
	Technology complexity (B16)	0.0/0.0/0.0	0.2/0.2/0.0	0.5/0.2/0.5	0.1/0.5/0.3	0.2/0.1/0.2	0.0/0.0/0.0	0.0/0.0/0.0
	Difficulty of operation and management (B17)	0.0/00/0.0	0.3/0.0/0.2	0.3/0.3/0.4	0.1/0.3/0.4	0.3/0.4/0.0	0.0/0.0/0.0	0.0/0.0/0.0
	Difficulty of rebuilding, expanding and upgrading (B18)	0.0/0.0/0.0	0.1/0.1/0.3	0.2/0.4/0.4	0.4/0.4/0.0	0.2/0.1/0.3	0.1/0.0/0.0	0.0/0.0/0.0
	Adaptability to sludge changes (B19)	0.2/0.0/0.1	0.5/0.0/0.3	0.1/.00/0.2	0.0/0.5/0.3	0.2/0.3/0.1	0.0/0.1/0.0	0.0/0.1/0.0

3. Results and Discussion

3.1. Carbon Emissions Accounting of Oily Sludge Treatment Technology

In order to promote the sustainable development of the world, carbon emission is an important environmental indicator to be considered when selecting oily sludge treatment technology. The process flow of incineration technology, chemical extraction technology and thermal desorption technology is shown in Figure 2. The specific energy consumption and material consumption are shown in Table 4.

The carbon emissions of incineration technology, chemical extraction technology and thermal desorption technology were 42.70 t CO_2-eq/t, 4.80 t CO_2-eq/t and 0.10 t CO_2-eq/t, respectively. It can be seen that the carbon emission of incineration technology is the highest, which is 483.6 times that of the thermal desorption technology. Therefore, incineration technology will produce a large amount

of greenhouse gases and accelerate global warming. In contrast, chemical extraction technology and thermal desorption technology have less carbon emissions and have a relatively small impact on the climate. When considering the carbon emission indicators, chemical extraction technology and thermal desorption technology that generate less greenhouse gases can be considered first.

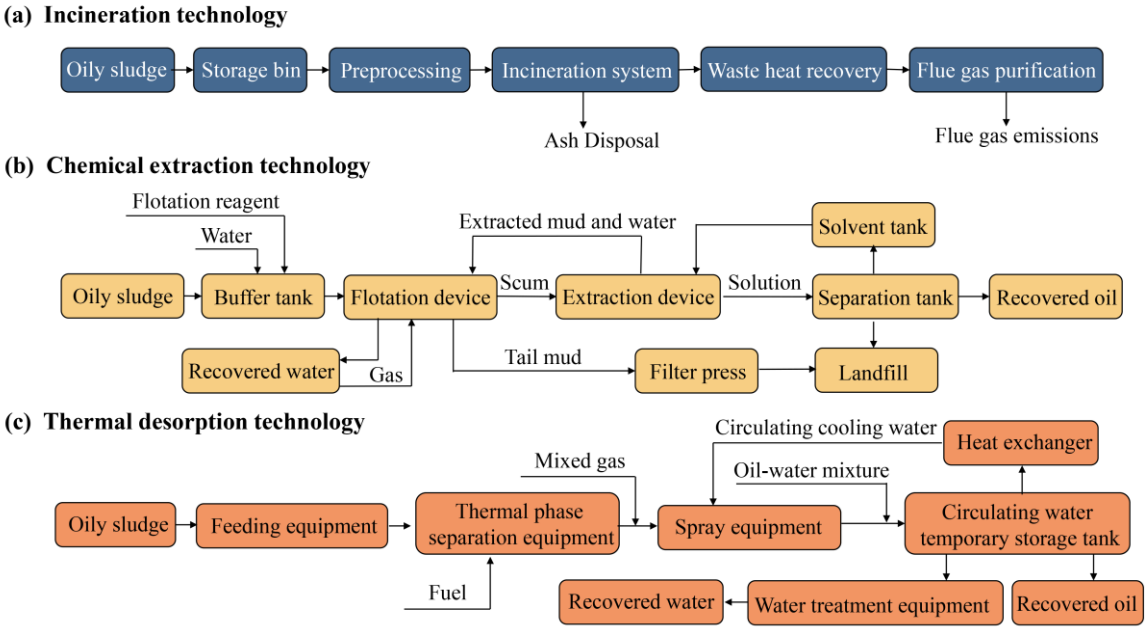

Figure 2. Oily sludge treatment process: (**a**) incineration technology; (**b**) chemical extraction technology; (**c**) thermal desorption technology.

Table 4. Carbon emissions accounting of three technologies.

Type	Project	Coefficient of Carbon Emissions	Craft List		
			Incinerate	Chemical Extraction	Thermal Desorption
Energy consumption	Electrical energy (KW·h)	0.0573 t CO_2/MW·h	146	0.88	28
	Natural gas (m^3)	2.66 kg CO_2/m^3	-	-	33
	Burning coal (kg)	2.53 kg CO_2/kg	336	-	-
	Diesel fuel (L)	2.73 kg CO_2/L	15300	-	-
Material consumption	Extraction potion (L)	1.60 kg CO_2/L	-	3000	-
Carbon emissions accounting (t CO_2-eq/t)		-	42.70	4.80	0.10

3.2. Evaluation of Oily Sludge Treatment Technology

According to the characteristics of oily sludge, such as great harm, high treatment difficulty and strong treatment timeliness, 4 primary indicators of environment, economy, society and technology and 19 secondary indicators of solid-phase oily environment compliance rate and secondary pollutant removal efficiency are determined. Through the statistically summarized the scores of each evaluation indicator, and normalize the score results to obtain the membership degree of each evaluation indicator.

On this basis, three mainstream oily sludge treatment technologies are selected for evaluation: incineration technology, chemical extraction technology, and thermal desorption technology. According to the fuzzy evaluation relationship matrix of each layer and the weight set of evaluation factors, the fuzzy comprehensive evaluation mathematical model is used in the calculation, and the evaluation scores and comprehensive evaluation scores of each index in the oily sludge treatment technology are obtained as shown in Table 5.

Table 5 shows that the environmental indicators account for 0.6173, the economic indicators account for 0.0565, the social indicators account for 0.2433, and the technical indicators account for 0.0829. Environmental and social impacts are a major concern due to the enormous pressure on environmental protection policies in countries around the world. Among the 19 weighted indicators, the weight of the compliance rate of the solid-phase oily environment is 0.4317, ranking first, which is consistent with the fact that oil content is the key emission indicator of many countries' environmental protection policy, where requirements for oily sludge treatment and discharge around the world are becoming more and more strict [32].

From the perspective of environmental benefit A1, the high-temperature incineration technology and thermal desorption technology scored higher on the B1 index, indicating that these two technologies can effectively reduce the oil content in oily sludge to 0.3%. However, the effect on the B3 index is not ideal, because the fly ash, flue gas generated during the combustion process and the exhaust gas generated during the thermal desorption process will cause secondary pollution [33]. Compared with the other two technologies, the extraction process of chemical extraction technology is a physical process, which does not produce new chemical pollutants, eliminates the risk of secondary pollution to the environment, and therefore scores higher on the B3 indicator.

Table 5. Weight of each factor in the indicator layer to the target layer.

Criterion	Indicator	Weight	Incineration Technology	Chemical Extraction Technology	Thermal Desorption Technology
A1	Solid-phase oil-bearing environment compliance rate (B1)	0.4317	6.0	5.3	6.1
	Wastewater environmental compliance rate (B2)	0.0396	3.8	4.5	3.7
	Secondary pollutant removal benefit (B3)	0.1459	3.2	5.2	3.9
A2	Infrastructure investment cost (B4)	0.0234	3.4	3.9	3.6
	Transportation cost (B5)	0.0042	3.1	4.7	4.3
	Operating cost (B6)	0.0031	3.5	3.8	4.4
	Unit sludge treatment cost (B7)	0.0017	3.0	4.4	3.7
	Crude oil recovery rate (B8)	0.0152	1.6	5.7	3.3
	Additional benefits of by-products (B9)	0.0089	1.8	5.3	4.2
A3	Workforce impacts (B10)	0.0129	3.1	4.9	4.3
	Policy and Regulation Impact (B11)	0.1256	4.4	5.1	4.6
	Impact on the surrounding environment (B12)	0.0763	3.0	5.5	3.4
	Resource recycling indicator (B13)	0.0285	1.8	5.2	3.9
A4	Floor space (B14)	0.0350	3.5	5.3	4.1
	Technology maturity (B15)	0.0207	5.4	5.1	5.4
	Technology complexity (B16)	0.0060	4.7	4.5	4.3
	Difficulty of operation and management (B17)	0.0115	4.6	3.9	4.8
	Difficulty of rebuilding, expanding and upgrading (B18)	0.0066	4.0	4.5	4.7
	Adaptability to sludge changes (B19)	0.0031	5.5	3.2	5.0
	Scores	-	4.59	5.16	4.95

From the perspective of economic benefit A2 and social benefit A3, the high-temperature incineration technology has a serious waste of resources due to the large energy consumption, and the difficulty in recycling heat and crude oil [22]. Therefore, the specific indicators of B4–B9 and B10–B13 scored the lowest. Due to the high operating temperature of thermal desorption technology, the quality of recovered oil is poor, and the score of B8 index is low. Because the chemical extraction technology maintains the original performance of crude oil and has a high recovery rate, it scores high on the indicators of B8 and B9, and maximizes the value of resource utilization [23]. In terms of social benefits, both technologies belong to the mainstream technology of oily sludge reduction [21,24,34].

From the technical aspect of A4, the incineration technology has high scores in B15, B16 and B19 indicators, suggesting that the technology is mature and has good adaptability to sludge, but there are also problems such as the large area of the whole set of equipment and the difficulty of reconstruction and expansion. Thermal desorption technology is relatively mature and has good adaptability to sludge, so it scores higher on B15 and B19 indicators. However, there are also problems such as complex installation and harsh control conditions, and the score is low in the B16 indicator. Comparatively speaking, the chemical extraction technology has higher scores in B14, B15 and B16 indicators, indicating that the technology occupies a small area, the technology is relatively mature, and it is easy to implement [35].

Based on the above analysis, the three oily sludge treatment technologies have their own advantages and disadvantages in these 19 indicators. According to the quantitative comprehensive evaluation scores obtained by the AHP-FCE method, the incineration technology scored 4.59, the chemical extraction technology scored 5.16, and the thermal desorption technology scored 4.95. Therefore, it is more advantageous to choose the chemical extraction technology with the highest comprehensive score. However, due to the different actual situation of each oil and gas field enterprise, the emphasis of each index factor in the index layer is also different, so the corresponding oily sludge treatment technology can be selected according to its score.

4. Conclusions

Taking the current three mainstream oily sludge treatment technology as an example, this paper considers the impact of carbon emissions on the environment, and then tests the physical and chemical properties of oily sludge through experiments to determine the evaluation index of oily sludge treatment technology. The AHP-FCE method is used to calculate the comprehensive score, and the following conclusions are obtained:

(1) By analyzing the impact of oily sludge treatment technology on the environment, the carbon emissions of the three technologies were calculated using the emission factor method. Among them, the highest carbon emissions of incineration technology were 42.70 t CO_2-eq/t, the lowest carbon emissions of thermal desorption technology were 0.10 t CO_2-eq/t and the carbon emissions of chemical extraction technology was 4.80 t CO_2-eq/t. thermal desorption technology and chemical extraction technology with lower carbon emissions are preferred. Because the greenhouse effect is closely related to gases such as carbon dioxide, thermal desorption technology and chemical extraction technology with low carbon emissions are favored.

(2) When AHP-FCE method was used for comprehensive evaluation, the highest score of chemical extraction technology was 5.16, the lowest score of high temperature incineration technology was 4.59, and the score of thermal desorption technology was 4.95. Due to the continuous improvement of people's awareness of environmental protection, high temperature

incineration technology will be gradually eliminated; thermal desorption technology is suitable for oily solid wastes which are difficult to be treated, such as impurities and complex components. Chemical extraction technology is the best choice, which is suitable for the treatment of high oil content solid waste, and the value of resource recovery is very high.

(3) The comprehensive application of carbon emission evaluation and AHP-FCE evaluation is a scientific and reasonable research method. The chemical extraction technology with relatively low carbon emission and the highest comprehensive technical score is the best oily sludge treatment method, which can provide theoretical reference for technicians to choose oily sludge treatment technology.

Acknowledgments

The authors acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 52100135), Sichuan University Postdoctoral Interdisciplinary Innovation Fund (Grant No. JCXK2207), and the Young Elite Scientists Sponsorship Program by CAST (Grant No. 2022QNRC001).

Author Contributions

Conceptualization, Jiwei Wu and Liang Ma; Methodology, Jiwei Wu; Software, Shifan Zhang and Jian Li; Validation, Haocheng Sun, Zixian Jia and Ye Xia; Formal Analysis, Jianqiang Sun; Investigation, Jiankun Liu; Resources, Jie Liu and Dongliang Pan; Data Curation, Xianzhong Yi; Writing – Original Draft Preparation, Jian Li and Shifan Zhang; Writing – Review & Editing, Jiwei Wu and Liang Ma; Visualization, Shifan Zhang and Jian Li; Supervision, Jiwei Wu; Project Administration, Jiwei Wu; Funding Acquisition, Jiwei Wu.

Funding

This research was funded by [National Natural Science Foundation of China] grant number [52100135], [Sichuan University Postdoctoral Interdisciplinary Innovation Fund] grant number [JCXK2207] and [Young Elite Scientists Sponsorship Program by CAST] grant number [2022QNRC001].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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