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Analysis of Hazardous Waste Management Elements in Oil and Gas Enterprises Based on the Life-Cycle Management Concept

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Abstract: By analyzing the China's hazardous waste management policy and the existing problems in hazardous waste management, the elements of hazardous waste management in oil and gas exploration enterprises were identified. Based on the theory of life-cycle management under the concept of sustainable development, combined with literature research, a three-level comprehensive index system was constructed by using the AHP–entropy weight method to evaluate the hazardous waste management capability of oil and gas enterprises. It was proposed that oil and gas enterprises should further strengthen the life-cycle management of hazardous waste, strengthen the assessment of hazardous waste management capacity, continuously establish a sound hazardous waste supervision system, and actively build a hazardous waste information control platform to realize the whole-process tracking management, as well as other suggestions.

Keywords: hazardous waste management; life-cycle management; evaluation system; AHP–entropy weight method

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1. Introduction

On 22 December 2021, in order to implement the Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste (2020 Revision), strengthen the environmental management of hazardous waste in key industries, and guide relevant units to enhance the standardized environmental management of hazardous waste, the Ministry of Ecology and Environment of China published a series of documents entitled "Guidelines on the Environmental Management of Hazardous Waste" in seven key industries, containing guidelines for onshore oil and gas extraction, lead and zinc smelting, copper smelting, coking, industrial waste salt, hazardous waste incineration and disposal, and steel rolling and processing [1]. The onshore oil and gas extraction industry generates a large amount of hazardous waste, and there is a greater risk of pollution in the process of utilization and disposal, and the oil and gas extraction process generates a large variety of hazardous waste with complex components. Improving the effectiveness of the environmental management of hazardous waste in the oil and gas extraction process is an urgent need for oil and gas enterprises at this stage. With the continuous development of the oil and gas exploration and development business, the environmental problems caused by hazardous wastes have gradually come to the fore. Therefore, the prevention and control of hazardous waste pollution in the oil and gas industry and the strengthening of hazardous waste management in oil and gas enterprises are of great practical significance to protect the ecological environment, guarantee the green development of the oil and gas extraction industry, and support the long-term and stable development of oil and gas enterprises.

To effectively strengthen the management of hazardous waste in oil and gas enterprises, a sound hazardous waste management system needs to be established. This paper mainly was carried out using qualitative content analysis as a research method, analyzed the focus of hazardous waste management according to the hazardous waste management policy text of China, and constructed the hazardous waste management elements of oil and gas enterprises. We combined the theory of life-cycle management, comprehensively considered each stage of hazardous waste from generation to disposal, that is, the generation, collection, transportation, transfer, recycling, and reuse of hazardous waste to final disposal, as well as the use of substances and energy included in each stage, and quantified its input (raw materials, resources and energy) and output (emissions). We comprehensively considered the material and energy utilization efficiency at each stage and the impact of the discharged waste on the environment, with the aim to design an environmentally effective, economically feasible, and socially acceptable evaluation index of hazardous waste management capacity. As a first step, based on the national hazardous waste statistics and the main types of hazardous waste in the oil and gas industry, we analyzed the problems in the current hazardous waste management in the oil and gas mining industry through literature research, and analyzed the key points of hazardous waste management in the oil and gas mining industry using the text of the hazardous waste management policy as a reference for the enterprise's hazardous waste management evaluation indicators. The second step was to establish the evaluation index system in the AHP–entropy weight method of hazardous waste management capacity of oil and gas enterprises based on relevant literature research and the concept of life-cycle management, with the aim being to provide a reference for the improvement of hazardous waste management in oil and gas extraction enterprises.

2. Literature Review

Life-Cycle Management of Hazardous Waste

Hazardous waste is solid waste with hazardous characteristics and that is listed on the national hazardous waste list or identified according to the national hazardous waste identification criteria and identification methods [2]. Hazardous waste causes a high degree of pollution to the soil, water, and atmosphere, and places a heavy burden on the effective management of the environment.

Hazardous waste management refers to the use of legal, administrative, economic, technical, and other means to solve the negative impact of hazardous waste on the environment. At present, there are two main types of international hazardous waste management systems. One is the priority management system of hazardous waste established by some western developed countries and regions. The United States, the EU, New Zealand, and other countries established a priority management list based on the toxicity and production status of hazardous waste or chemicals, and strictly control and focus on the management of key hazardous wastes with serious hazards. Another group of countries, represented by Japan, have classified hazardous wastes based on different responsible subjects of industrial sources and social sources to facilitate the implementation of each responsible subject. According to the sources of hazardous waste, the current management methods for relevant enterprises include hierarchical management system, environmental pollution liability insurance system, etc. Key and feasible measures are proposed from different aspects of hazardous waste management, which not only reduces the burden of enterprises, but also improves the level of hazardous waste management of government environmental protection departments [3,4]. Although China has also formulated some laws and regulations on hazardous waste management at present, there is a lack of innovation in the specific implementation rules. Because of the imperfect enterprise hazardous waste management system and low level of disposal and utilization, the level of hazardous waste management needs to be improved.

To achieve the safe disposal of hazardous waste, enterprises must optimize their management from a life-cycle perspective. Although life-cycle management is not a standardized discipline, it is an overall framework that can combine and apply other management tools from a more holistic life-chain perspective. The advantage of life-cycle management is that it can more clearly consider the upstream and downstream impacts, and it can provide guidance for enterprises to design management tools from the perspective of system dynamics [5].

Life-cycle management is the management of information and processes throughout the life-cycle of a product, from planning and design, production and distribution, consumption and use, to recycling and disposal [6]. Based on life-cycle management thinking, enterprises need to consider the economic, environmental, and social impacts of products throughout their life-cycle from design and production to recycling and disposal so that they can meet market demand and operational efficiency while finding opportunities to achieve sustainable development and reduce negative impacts on the environment. The application of life-cycle management theory has expanded and enriched with the progress of human society, gradually extending from single products to enterprises and industries. In this process, the division of the different stages of the life-cycle of products has gradually become clear, and the costs, energy, and resource consumption and environmental impact of each stage have been refined, analyzed, and measured accordingly. From the perspective of environmental management, it is important to integrate the concepts of green design, green production, green consumption, and green development into the life-cycle [7].

In the whole life-cycle stage, hazardous waste management is in the recycling and disposal stage, but if we only focus on this stage, we cannot make hazardous waste management run through all stages of an enterprise's life-cycle, and many policy, mechanism, and technology issues will be difficult to solve [8]. To move beyond the static and rigid management model, it is necessary to plan whole industry chain, to manage from the perspective of the life-cycle, and to solve the problem of poor articulation and coordination of institutional mechanisms. Life-cycle management is carried out over a large time span, covering a wide range of management modes, and must comprise green, ecological, recycling, and other concepts throughout the life-cycle management of hazardous waste, as well as pay attention to each stage and link of energy consumption and pollution, integrated energy saving, environmental protection, the economy, and many other factors [9]. Therefore, based on life-cycle management's goal to optimize hazardous waste management, we should start from the source of enterprise production, carry out green design, implement clean technology, pay attention to the comprehensive use and recycling of materials in the manufacturing process, promote green circulation, storage, and consumption and to the comprehensive use and harmless disposal of hazardous waste, and scientifically plan the cost, energy consumption, and environmental disposal methods of the whole industrial chain [10].

3. Methods and Materials

The quality of the hazardous waste disposal capacity of oil and gas enterprises determines the high-quality development of oil and gas enterprises. Taking the hazardous waste disposal capacity of oil and gas enterprises as the research object, with reference to relevant national policies, a textual analysis method and literature research method were used to build an evaluation index system for determining the hazardous waste disposal capacity of oil and gas enterprises exploring the current situation and existing problems of the hazardous waste disposal capacity of oil and gas enterprises from the perspective of life-cycle management.

3.1. Status of Hazardous Waste in China's Oil and Gas Extraction Industry

With the rapid development of China's economy and the rapid advancement of industrialization level, hazardous waste pollution problem is also becoming more and more prominent; all kinds of incidents regarding the illegal disposal of hazardous waste also occur from time to time. The comprehensive use and safe disposal of hazardous waste has become a prominent problem plaguing economic and social development. From the perspective of hazardous waste generation, the Ministry of Ecology and Environment's Annual Report on China's Ecological and Environmental Statistics 2020 showed that, in

2020, the national industrial hazardous waste generation comprised 72,818,000 tons and utilization and disposal comprised 76,305,000 tons of waste. From a regional perspective, the top five regions in terms of industrial hazardous waste generation are Shandong, Inner Mongolia, Jiangsu, Sichuan, and Zhejiang, accounting for 12.8%, 7.4%, 7.2%, 6.3%, and 6.1% of the national industrial hazardous waste generation, respectively. Industrial hazardous waste utilization and disposal of the top five regions in Shandong, Yunnan, Jiangsu, Inner Mongolia, and Zhejiang, respectively, account for 13.2%, 11.6%, 6.9%, 6.3% and 6.1% of the national industrial hazardous waste utilization and disposal. From the industry point of view, the types of industrial hazardous waste generated by the top five industries are in the following order in terms of prevalence: chemical raw materials and chemical product manufacturing, non-ferrous metal smelting and rolling processing, petroleum, the processing of coal and other fuels, ferrous metal smelting and rolling processing, electricity, and heat production and supply. The five industries of industrial hazardous waste generation account for 69.6% of industrial hazardous waste generation, of which petroleum, coal, and other fuel processing industries accounted for 12.8%. The industrial hazardous waste utilization and disposal prevalence of the top five industries is in the following order: non-ferrous metal smelting and rolling processing, chemical raw material and chemical product manufacturing, petroleum, coal and other fuel processing, ferrous metal smelting and rolling processing, electricity, and heat production and supply. These five industries of industrial hazardous waste utilization and disposal account for 75.5% of the national industrial hazardous waste utilization and disposal, including petroleum, coal, and other fuel processing industries, and other fuel processing industries accounted for 12.3% [11].

The oil and gas exploitation industry has a certain particularity. Although some wastes are defined as hazardous wastes, they still have high reuse value, for example, waste mineral oil, waste organic solvents, waste catalysts, and so on. After these hazardous wastes are smelted or purified, valuable resources can be extracted from them. For example, waste mineral oil and waste organic solvents can be reused after distillation and extraction, different waste catalysts can be revived by different processes, etc. According to China's document "Guidelines on the Environmental Management of Hazardous Waste-Onshore Oil and Gas Extraction" [1], the main hazardous wastes generated during the oil extraction process are shown in Table 1.

Table 1. Main hazardous wastes generated during oil and gas extraction.

Name of Waste	Generating Links	Appearance	Characteristic Pollutants	Generating Patterns
Waste oil-based drilling mud	Drilling sessions	Semi-solid	Waste mineral oil	Continuous generation
Oil-based rock waste	Drilling sessions	Solid	Waste mineral oil	Continuous generation
Landing oil	Downhole operations, oil recovery, gathering, and processing	Semi-solid and solid	Waste mineral oil	Intermittently generated
Tank-cleaning oil sludge	Oil extraction, gathering and processing	Semi-solid	Waste mineral oil	Intermittently generated
Oil slicks, scum, sludge	gathering and processing	Semi-solid and solid	Waste mineral oil	Continuous generation
Pigging residual waste	gathering and processing	Solid	Mineral oil	Intermittently generated
Filter adsorption media waste	gathering and processing	Solid	Waste mineral oil	Intermittently generated

Table 1. *Cont.*

Name of Waste	Generating Links	Appearance	Characteristic Pollutants	Generating Patterns
Impermeable material waste	Site clearance	Solid	Waste mineral oil	Intermittently generated

3.2. Problems in the Management of Hazardous Waste in the Oil and Gas Extraction Industry

At present, the following problems still exist in the management of hazardous waste in the oil and gas extraction industry in China:

(1) A long-term mechanism for hazardous waste management has not been formed. At present, "waste minimization, waste valorization, environmentally sound management" is the basic principle for the prevention and control of solid waste and hazardous waste pollution in China, but it lacks legal connotation and clear boundaries, is a relatively general required principle, is difficult to manage with unified standards, and lacks an operable indicator system [12]. China's hazardous waste disposal has long been at the end of the management stage; hazardous waste, as a solid waste with dangerous characteristics and large generation, requiring specific regulations, standards, guidelines, and so on, that can be used for practical operations still needs to be refined and improved. Overall, a systematic hazardous waste treatment and disposal mechanism based on the whole category and the whole life-cycle has not yet been formed [13];

(2) Hazardous waste treatment technology is still immature. The hazardous waste of oil sludge, which is generated in large quantities in China, for example, drilling oil sludge and tank sludge, is larger in quantity and relatively well disposed of. Socially collected oil sludge is more mixed and contains more harmful substances, which makes disposal more difficult. Domestic oil sludge disposal technology is of two types: burning and separation. Three-phase separation technology is also known as the water washing process, and the process can be divided into pharmaceutical cold separation and pharmaceutical hot separation. The pharmaceutical hot separation process is more practical for oil produced in oil fields and oil sludge produced by tank cleaning, but most enterprises do not really use this process well because there is no equipment in the industry that properly meets the process requirements. At present, the industry's more technologically advanced oil sludge disposal technology can perform well in pilot trials, but cannot achieve the same results in actual production projects. The current methods of oil sludge disposal are varied but not sufficiently mature. The complex origin of the oil sludge makes it difficult to have a process that is well adapted. Strictly speaking, the disposed oil sludge hardly meets the national requirements. The temperature requirement for oil sludge sintering is high, but it is difficult for companies to sinter above 800 °C. It is difficult to turn the harmful organic matter in the oil sludge into harmless material at a high temperature of 800–1000 °C [14];

(3) An inter-industry and inter-regional synergistic disposal mechanism has not been formed. The disposal of hazardous waste in different areas has long been managed by administrative divisions, each based on local interests, and there are certain regional contradictions in the generation and disposal of hazardous waste. Hazardous waste disposal facilities in some areas are operating at full capacity, but some areas have relatively sufficient hazardous waste disposal capacity, and a good cross-regional coordination of hazardous waste disposal has not yet formed a shared mechanism of common governance. At present, units with hazardous waste operation licenses nationwide are mainly concentrated in the Yangtze River Delta and Pearl River Delta regions, while the treatment capacity in key provinces such as Shandong and Inner Mongolia, where hazardous waste is discharged, is relatively insufficient. In terms of management, the storage, collection, and transportation of hazardous waste lack perfect institutional arrangements, and many places still adopt improper paper-based

management of hazardous waste transfer coupons, which can be easily falsified and changed, making supervision difficult. At the same time, the regulatory force of hazardous waste is weak and there is a lack of supervisory personnel, especially at the district and county levels, which lack specialized hazardous waste management personnel [15].

(4) Hazardous waste is difficult to recycle, difficult to treat and dispose of, and has a low reuse rate. Compared with primary resources, hazardous waste is characterized by complex and variable properties, high pollutant content, and low resource quality [16]. The use of hazardous waste consumes material and energy, and there must be new material and energy input, that is, to pay the corresponding economic costs; at the same time, new pollution emissions are produced, that is, to pay the corresponding environmental costs. Some technologies in the hazardous waste industry that claim to be able to achieve zero pollution and zero emissions are in fact contrary to the laws of science. On the surface, they solve a difficult problem, but in essence they increase the environmental risk, and while the cost of treatment increases significantly, the overall level of pollutant emissions and environmental risk increases rather than decreases. The resource utilization of hazardous waste is conditional, and a balance between environmental, social, and economic benefits must be achieve [17].

3.3. Policy Elements of Hazardous Waste Management

Management elements refer to the necessary factors that constitute management activities. Policy elements play an important role in guiding the government, enterprises, and society in conducting management activities, and the analysis of policy elements related to hazardous waste management can be conducted to draw certain hazardous waste management elements from them, which is conducive to achieving the legitimacy and effectiveness of hazardous waste management. The policy texts on hazardous waste management collected in this study were mainly sourced from the China Laws & Regulations Database, supplemented by policy texts mentioned in relevant academic literature in order to obtain more comprehensive policy text data. To ensure the consistency of the textual data and the feasibility of the study, the policy documents issued by the central government of China between 2000 and 2021, which represent the overall will of the country, were selected for this study. After data retrieval, manual reading, and sifting, 58 policy documents on hazardous waste management were finally obtained. The texts that mentioned policy effect and which are highly relevant to hazardous waste work, such as administrative regulations and departmental rules, were selected. The texts that are currently in force were selected, and those that are no longer valid were excluded. The main forms of policy issuance were circulars, announcements, and management measures, and texts in the form of reply letters and approvals were excluded [18].

In this study, the collected policy text data were integrated, a word separation process was carried out to extract high-frequency words, and then words that were not practically meaningful to this study were eliminated. After the screening of high-frequency words, the PriceLaw $M = 0.749 * (Nmax)^{0.5}$ was used for validation, where Nmax was the most frequent word in this group. The frequency of "hazardous waste" was 2041, and it was determined that the minimum frequency of words that could be used as core subject words at this stage should be approximately equal to 34, i.e., high-frequency words that occurred 34 times or more could be considered as core subject words. The partial core words are shown in Table 2 in order of frequency.

The basic principle of co-occurrence analysis is to count the number of occurrences of a number of words in the same text, cluster these words, analyze the network relationships between them, and then analyze the structural changes in the themes of the text content they represent. The higher the co-occurrence of two words, the more closely related the words are to each other. In this study, a matrix of core topic words co-occurring in hazardous waste policy texts from 2000 to 2021 was constructed using a self-written program in Python3.8. Because of space constraints, Table 3 presents a partial matrix of the top eight most frequent topic words in the matrix as an example.

Table 2. Core subject headings for hazardous waste management policy texts, 2000–2021 (partial).

High-Frequency Word	Word Frequency	High-Frequency Word	Word Frequency	High-Frequency Word	Word Frequency
hazardous waste	2401	storage	282	evaluation	190
treatment	1088	incinerate	279	acceptance	184
facility	614	pollution	271	running	179
medical waste	409	technology	257	monitor	175
project	364	identify	250	environmental impact	174
management	360	ecosystem	237	report	173
standard	339	system	231	ability	172
utilization	318	environmental protection	204	information	168
surroundings	308	solid waste	202	landfill	167
transfer	286	forward planning	198	operate	157

Table 3. Matrix of core subject term co-terminology for hazardous waste management policy texts, 2000–2021 (partial).

	Hazardous Waste	Treatment	Facility	Medical Waste	Project	Management	Standard	Utilization
hazardous waste	1550	580	302	219	66	204	131	185
treatment	580	781	297	228	63	65	44	200
facility	302	297	482	149	40	28	28	36
medical waste	219	228	149	318	33	4	18	3
project	66	63	40	33	274	11	4	6
management	204	65	28	4	11	301	10	22
standard	131	44	28	18	4	10	283	0
utilization	185	200	36	3	6	22	0	269

This matrix was imported into the software Ucinet 6.0 and a network diagram of the core subject word co-terminology of this phase of the hazardous waste policy text was drawn with the aid of the tool NetDraw2.084 as shown in Figure 1.

The core words of China's hazardous waste management policy elements are as follows: treatment, facility, medical waste, project, management, standard, utilization, environment, transfer, storage, incineration, pollution, technology, identification, ecology and environment, system, environmental protection planning, evaluation, acceptance, monitoring, environmental impact, etc. Overall, China's hazardous waste management policy system is on the rise, and a lot of work has been carried out in the planning and construction of institutional mechanisms for hazardous waste management, preparation of hazardous waste management standards, hazardous waste flow, utilization and disposal, hazardous waste-related technology research, hazardous waste environmental risk control and management, cultivation of regional key facilities, etc. Medical waste is the key sector of concern in hazardous waste. The National List of Hazardous Waste has been updated since January 2021, which plays an important role in guiding the determination of the properties of solid waste after utilization and disposal. The new Trial Implementation of the Measures for the Management of Hazardous Waste Transfers in 2022 further strengthens the supervision and management of hazardous waste transfer activities, and the competent ecological and environmental departments, transport authorities, and public security organizations strengthen collaboration and share information on hazardous waste transfer coupons and transport. These policy elements reflect the need to strengthen joint supervision. Vertically, these policy elements reflect the deepening of hazardous waste management capacity building from the whole to the local [19,20].

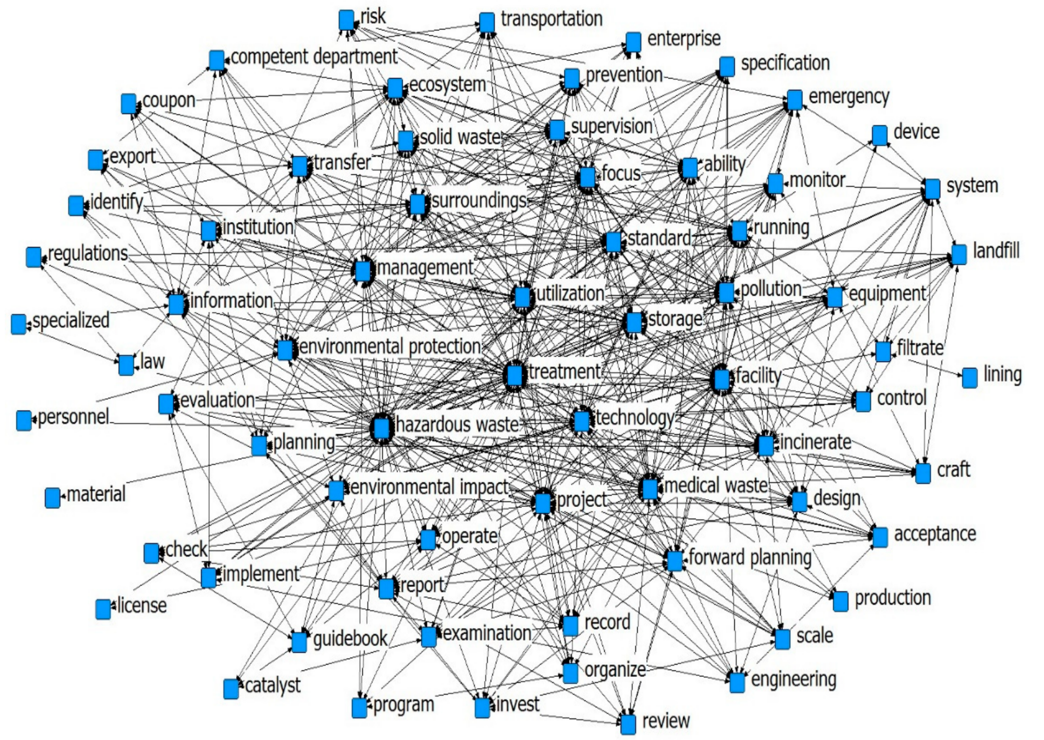

Figure 1. Co-term network of core subject terms in hazardous waste management policy texts 2000–2021.

3.4. Elements of Life Management in the Oil and Gas Extraction Industry

To optimize the management of hazardous waste in the oil and gas extraction industry, based on the elements of hazardous waste management policy, it is necessary to go further to establish a whole process management mindset and analyze the management elements from the perspective of the whole oil and gas industry chain. To this end, based on the concept of life-cycle theory, the elements of hazardous waste management in the oil and gas extraction industry are summarized as follows: hazardous waste source control, hazardous waste regulatory institutional mechanism, hazardous waste collection and transfer process supervision, hazardous waste disposal facility construction, hazardous waste utilization and disposal technology development, and hazardous waste environmental risk prevention and control:

(1) In terms of hazardous waste source control, enterprises should strictly implement a hazardous waste identification system, strict environmental access, implement environmental impact assessment requirements, scientifically evaluate the hazardous waste generated by the construction projects, propose practical pollution prevention measures, and actively pretreat the hazardous waste. After the completion of the hazardous waste disposal project, the types, quantities, and utilization and disposal methods of hazardous waste shall be more closely connected with the national classified management directory and relevant technical specifications. Enterprises shall develop and promote production processes and equipment to reduce the amount of hazardous waste generated and the harmfulness of hazardous waste, and reasonably plan hazardous waste treatment facilities and paths [21–23];

(2) In terms of a hazardous waste regulatory institutional mechanism, enterprises should establish and improve the regulatory system and mechanism for hazardous wastes in the oil and gas exploration industry, explore a diversified governance model, perform their regulatory responsibilities for hazardous wastes in accordance with laws and regulations, strengthen coordination and cooperation among departments, further expand the channels of communication and cooperation between departments, timely

report and coordinate major issues in hazardous waste supervision, and promote information sharing. Enterprises should implement responsibility; the main person in charge of the enterprise is the first person responsible for the prevention and control of hazardous waste pollution and safe production, and for establishing and improving the responsibility system for pollution prevention and safe production [24];

(3) In terms of hazardous waste collection and transfer process supervision, the collection and transfer of storage requires continuous professional improvement to make the transfer and transportation convenient. Enterprises should establish a record-keeping system for hazardous waste transport vehicles, and strengthen the risk control of long-distance transportation of hazardous waste, strictly deal with hazardous waste environmental violations and criminal acts and evasion of supervision, implement an ecological environment damage compensation system, and ensure financial investment in hazardous waste identification and standardized storage [25];

(4) In terms of hazardous waste disposal facility construction, enterprises should strengthen the construction of hazardous waste landfills and their disposal capacities, and study and formulate a list of hazardous waste landfill access, coordinate the management of hazardous waste disposal facilities, actively assess the match between hazardous waste generation and disposal capacity and the operation of facilities, actively promote the use of multiple disposal sites of hazardous waste, study and promote the application of high-temperature melting and other advanced technologies, and accelerate the construction of cement kilns, industrial kilns, and other co-disposal methods of hazardous waste facilities [25];

(5) In terms of hazardous waste utilization and disposal technology, enterprises should actively promote the large-scale development and professional operation of hazardous waste utilization and disposal units, encourage diversified investment and market-oriented approaches to the construction of large-scale facilities for the utilization of hazardous wastes, accelerate the popularization and application of advanced and applicable technologies, and focus on the research, demonstration, and promotion of applicable technologies for the utilization and disposal of hazardous wastes and the prevention and control of environmental pollution, improve basic research capabilities, and support research activities related to the hazardous waste environment, conduct research on the identification and control mechanism of environmental risks of hazardous wastes, and strengthen the capacity building of regional hazardous wastes and chemical testing and analysis [26];

(6) In terms of hazardous waste environment risk prevention and control, enterprises should establish a hazardous waste supervision system that matches the needs of environmental risk prevention and control, strengthen the construction of a professional risk prevention and control team, improve the hazardous waste supervision ability and technical capacity for emergency disposal, strengthen the comprehensive law enforcement team and capacity for building ecological environment protection, strengthen the construction of the professional talent team and expert pool, and implement the management of a hazardous waste business license, transfer management system, and hazardous waste storage standards and specifications for pollution control in incineration and identification [27].

4. Results and Discussion

4.1. Evaluation Index System for Hazardous Waste Management Capacity of Oil and Gas Enterprises

In terms of the construction of the index system, following the principles of objectivity, hierarchy, and comparability, the "management capability evaluation of oil and gas enterprises" consistent with the research theme was selected as the subject word for literature retrieval, and finally more than 270 papers related to the research theme were obtained. The literature summary, evaluation indicators at all levels, literature sources, and other related contents of the effective literature were classified and sorted to form the basic literature data. The text analysis method was used to analyze the word frequency, semantic fit with research objectives, and indicator marking results of evaluation indicators in policy documents and related papers. At the same time, we consulted and referred to the major oil and gas corporate social responsibility reports, environmental, social, and governance reports, sustainable development reports, corporate annual reports, and other practice reports, and paid attention to the strategic layout related to the development of solid waste disposal of enterprises and relevant performance indicators of enterprises. Finally, the evaluation index system of the hazardous waste management capacity of oil and gas enterprises was established based on the text analysis results.

In order to implement the responsibility of hazardous waste management in oil and gas enterprises, improve the efficiency of resource utilization, and strengthen the pollution prevention of hazardous waste in oil and gas enterprises, it is important to establish an evaluation index system for hazardous waste management capability in oil and gas enterprises [28]. The AHP–entropy weight method is a comprehensive evaluation method combining the analytic hierarchy process and entropy weight method. AHP can comprehensively analyze people's subjective qualitative judgment and form the weight of each decision making factor [29–31]. The entropy weight method is used to measure the information amount of data by calculating the information entropy of indicators, and determine the weight of indicators according to the impact of the relative change of indicators on the whole. It is an objective method of weighting. The AHP–entropy weight method combines the advantages of both and makes up for their shortcomings. The AHP–entropy weight method can not only reflect the actual experience of experts, but also use the survey data to finally obtain more accurate and reasonable evaluation results. This method is applicable to the evaluation of the hazardous waste management capacity of oil and gas enterprises [32–34]. In this paper, by analyzing the national policy elements of hazardous waste management, combining the life-cycle management elements and industry characteristics of the oil and gas extraction industry, and following the principles of objectivity and wholeness, the AHP–entropy weight method was adopted to construct an evaluation index system of the hazardous waste management capability of oil and gas enterprises, as shown in Table 4.

Table 4. Three-level indicator system for evaluating the capacity of oil and gas enterprises to manage hazardous waste.

First-Level Indicators	Second-Level Indicators	Third-Level Indicators
Institutional indicators	Coherence indicators	the degree of coordination of the internal organizational structure of the hazardous waste management system; the management ability to discover the value of green technologies for hazardous waste treatment; the degree of operation of the management planning system; the completeness of the emergency planning system; the soundness of the incentive mechanism; the utilization rate of environmental protection investment; the growth rate of investment in green technologies for hazardous waste treatment; the scale of venture capital investment in green technologies for hazardous waste treatment; the amount of green technology innovation results; the sharing rate of hazardous waste information among enterprise units
	Adequacy indicators	the knowledge level of hazardous waste management specialists; the clarity of property rights and protection of green technologies for hazardous waste treatment; the awareness of competition in hazardous waste treatment technologies; the number of environmental protection specialists, the turnover rate of hazardous waste management talents; the proportion of direct funds used for hazardous waste management; the level of the operating license system; the level of the labeling system; the level of the declaration and registration system; the level of the transfer coupon system; the level of the storage management system; the level of utilization and disposal facility management; the soundness of the operation's safety system; the level of recording and reporting operations

Table 4. *Cont.*

First-Level Indicators	Second-Level Indicators	Third-Level Indicators
Environmental control indicators	Energy use indicators	energy consumption for hazardous waste treatment; comprehensive disposal rate of hazardous waste; safe disposal rate of hazardous waste; reuse rate of water for hazardous waste treatment; share of new energy use in total energy consumption; ratio of low carbon materials in total material consumption
	Production technique indicators	cleaning product factor; total investment in hazardous waste treatment equipment; renewal rate of hazardous waste treatment equipment; proportion of advanced energy-saving and high-efficiency equipment among all equipment; stable and continuous operation capacity of hazardous waste treatment equipment; investment in research and development of hazardous waste treatment green technology; ratio of the output value of hazardous waste treatment green technology to the total output value of the enterprise; popularity rate of hazardous waste treatment training for operating staff
	Emission disposal indicators	annual emissions of hazardous waste; annual emissions of major water pollutants; annual emissions of major air pollutants; emissions of hazardous waste from production units of products; compliance rate of effluent and exhaust emissions from hazardous waste disposal; soil environmental quality index around hazardous waste disposal facilities; disposal rate of oily sludge
	Environmental benefit Indicators	the proportion of hazardous waste treatment cost to total cost; the proportion of investment return on hazardous waste treatment to total return; the return on investment and repayment period for individual major hazardous waste treatments; the return on investment for comprehensive hazardous waste treatment; the growth rate of economic benefits generated by low-carbon technologies; the matching degree between enterprise policies and national policies in hazardous waste treatment

As can be seen from Table 4, the indicators of hazardous waste management capacity of oil and gas enterprises are divided into three levels, with the first level indicator set $U = (U_1, U_2)$. Each first-level indicator is composed of second-level indicators, which can be expressed as $U_i = (U_{i1}, U_{i2} \ldots U_{ij})$, and each second-level indicator U_{ij} comprises the third-level indicators U_{ijk}. Using the analytic hierarchy process, from the research objectives, 10 representatives of senior experts who have long been engaged in petroleum engineering management, solid waste management, and environmental engineering management were selected and issued with opinion questionnaires to construct the judgment matrix of each level of the evaluation model of hazardous waste management capability of oil and gas enterprises. By constructing a comparative judgment matrix and the mathematical method of matrix operation [35], the importance ranking and relative weights of the elements related to them in this level were determined. This step mainly used expert scoring method to determine the weight C_{ij} between two elements. C = (C_{ij}), i = 1, 2, . . . n, j = 1, 2, . . . n, $C_{ij} = C_i/C_j$.

$$
\begin{matrix}
c_{11} & c_{12} & \cdots & c_{1n} \\
c_{21} & c_{22} & \cdots & c_{2n} \\
c_{31} & c_{32} & \cdots & c_{3n} \\
\cdots & \cdots & \cdots & \cdots \\
c_{n1} & c_{n2} & \cdots & c_{nm}
\end{matrix}
$$

In the matrix, C_{ij} denotes the importance of impact factor C_i in relation to impact factor C_j. The importance of these factors is expressed in numerical terms, using the "1–9 scale", with 1, 3, 5, 7, and 9 indicating the influence on the upper level of C_i is of the same importance, slightly important, obviously important, strongly important, and extremely important in relation to C_j, and 2, 4, 6, and 8 indicate the intermediate values of the adjacent judgements. Next, the constructed judgement matrix was calculated to yield the maximum characteristic roots of the judgement matrix.

$$\lambda_{max} = \frac{1}{n}\sum_{k=1}^{n}\frac{(Bw)_i}{w_i}$$

Then, the eigenvalues and eigenvectors of the matrix were found and tested for consistency. After constructing the judgment matrix, we obtained the relative weight matrix of impact factors $w = w_1,\ w_2,\ \ldots\ ,\ w_n$, then conducted consistency tests on the judgment matrix and calculated the deviation consistency index.

$$C.I. = \frac{\lambda_{\max} - n}{n-1}$$

The average random consistency index RI was checked and then the consistency ratio was calculated. The consistency ratio $CR = CI/RI$ was then calculated and the matrix was considered to have satisfactory consistency if $CR < 0.1$.

The steps of entropy weight method are as follows [36]:

(1) If the indicator system is assumed to contain m samples and n indicators, the original matrix can be expressed as follows:

$$\mathrm{R} = \left(r_{ij}\right)_{\mathrm{n}\times\mathrm{m}},\ \mathrm{i} = 1,\ 2,\ \ldots,\ \mathrm{n};\mathrm{j} = 1, 2, \ldots, \mathrm{m};$$

(2) The extracted data information were processed by a non-negative number, and the data value is processed by coordinate translation. For positive indicators, the following formula was used to calculate: r_{ij} = (Xij − Xmin)/(Xmax − Xmin);

For negative indicators, the following formula was used for calculation: $r_{ij} = (\mathrm{X_{max}} - \mathrm{X_{xj}})/(\mathrm{X_{max}} - \mathrm{X_{min}})$;

(3) The original matrix R was standardized, expressed as $\mathrm{P} = (\mathrm{P_{ij}})_{\mathrm{n}\times\mathrm{m}}$, and the proportion of the ith scheme was calculated in the index of item j, where $\mathrm{P_{ij}} = \mathrm{r_{ij}}/\sum_{j=1}^{m} r_{ij}$ stands for weight;

(4) We calculated the entropy value of index j:

$$e_j = -k\sum_{i=1}^{n} P_{ij} \cdot ln\left(p_{ij}\right)$$

where $k > 0$, ln is the natural logarithm, and $e_j \geq 0$. In the formula, the constant k is related to the number of samples m. Generally, let $k = k = 1/\ln m$, $0 \leq e \leq 1$;

(5) We calculated the difference coefficient of the jth index. For the jth index, the greater the difference of P_{ij}, the greater the evaluation and impact on the scheme, and the smaller the entropy. $g_j = 1 - e_j$, the bigger the g_j, the more important the index is;

(6) Weighting $W_j = \frac{g_j}{\sum_{j=1}^{m} g_j}$,j = 1, 2, . . . m was performed. W is the weight value and g is the difference coefficient.

4.2. Empirical Analysis

In this paper, the situation of four oil and gas enterprises was selected as an example of the indicator system of hazardous waste management capability, which is expressed as E_1, E_2, E_3, E_4. The data used were from the annual report of the enterprise, and the selected time was 2021. According to the indicator system constructed in this paper, 10 professional oil and gas industry practitioners and scientific researchers were selected to score the importance of each indicator in the six dimensions as shown in Table 5. According to the scoring, AHP was used to determine the indicator weight, followed by the objective weighting method. After dimensionless processing of the original data, the entropy weight method was used to calculate the weight of each index.

Table 5. Initial decision matrix of the hazardous waste management capability of oil and gas enterprises.

	Coherence Indicators	Adequacy Indicators	Energy Use Indicators	Production Technique Indicators	Emission Disposal Indicators	Environmental Benefit Indicators
E1	6	2.4	7	4	6	8
E2	10	3	28	8	6	10
E3	9	2.8	12	7	8	7
E4	13	3.5	19	8	6	6
Total	38	11.7	66	27	26	31

We standardized the original matrix and calculated the proportion of each indicator as shown in Table 6.

Table 6. The normalized matrix of the original matrix.

	Coherence Indicators	Adequacy Indicators	Energy Use Indicators	Production Technique Indicators	Emission Disposal Indicators	Environmental Benefit Indicators
E1	0.1578947	0.205128	0.1060606	0.153846	0.230769	0.258064516
E2	0.2631579	0.25641	0.4242424	0.307692	0.230769	0.322580645
E3	0.2368421	0.239316	0.1818182	0.230769	0.307692	0.225806452
E4	0.3421053	0.299145	0.2878788	0.307692	0.230769	0.193548387

We calculated $P_{ij}*ln(p_{ij})$ to obtain the entropy value of the index as shown in Table 7.

Table 7. The entropy matrix.

	Coherence Indicators	Adequacy Indicators	Energy use Indicators	Production Technique Indicators	Emission Disposal Indicators	Environmental Benefit Indicators
E1	−0.291446	−0.32495	−0.237973	−0.28797	−0.33839	−0.34956017
E2	−0.351316	−0.34897	−0.363767	−0.36266	−0.33839	−0.36496842
E3	−0.341138	−0.34221	−0.309954	−0.33839	−0.36266	−0.3360174
E4	−0.366955	−0.36102	−0.358471	−0.36266	−0.33839	−0.31785053
Total	−1.350855	−1.37715	−1.270165	−1.35168	−1.37782	−1.36839652

At constant k = $-1/ln_4 = -0.721348$, e_j is the entropy value and D_j is the difference level, while W is the weight value, as shown in Table 8.

Table 8. Calculation of the difference coefficient and weight value.

	Coherence Indicators	Adequacy Indicators	Energy use Indicators	Production Technique Indicators	Emission Disposal Indicators	Environmental Benefit Indicators
e_j	0.9744362	0.9934018	0.91623	0.9750319	0.9938867	0.987089439
D_j	0.0255638	0.0065982	0.08377	0.0249681	0.0061133	0.012910561
W	0.1598503	0.0412587	0.52381	0.1561253	0.0382265	0.08072953

Combining the decision matrix and weight value, the final score of the four enterprises can be calculated, of which E_2 had the highest score, indicating that its hazardous waste management ability was relatively good, as shown in Table 9.

Table 9. The scoring results of hazardous waste management capability of the four enterprises.

	Coherence Indicators	Adequacy Indicators	Energy use Indicators	Production Technique Indicators	Emission Disposal Indicators	Environmental Benefit Indicators	Final Score
E1	0.96	0.10	3.67	0.62	0.23	0.65	6.22
E2	1.60	0.12	14.67	1.25	0.23	0.81	18.67
E3	1.44	0.12	6.29	0.94	0.31	0.57	9.65
E4	2.08	0.14	9.95	1.25	0.23	0.48	14.14

According to the measured value of the hazardous waste management capacity level of oil and gas enterprises shown in Table 9, we can obtain the ranking of the current hazardous waste management capacity level of four enterprises: $E_2 > E_4 > E_3 > E_1$.

During the collection of evaluation index data and the calculation and evaluation of each index, it was found that E_2 had a relatively high level of hazardous waste management, its comprehensive disposal capacity of hazardous waste was in the leading position, and it had relatively advanced production technology and equipment, which largely guarantees the efficiency of hazardous waste treatment. However, E_2 should pay more attention to the improvement of the level of enterprise hazardous waste management specialists, the optimization of the concept of hazardous waste management, the improvement of the hazardous waste tracking system, and the strengthening of the requirements of the national policy on benchmarking, and contribute more efforts towards the emission of pollutants. The oil and gas industry has a wide range of hazardous waste types and quantities, and the life-cycle management concept is conducive to the optimal management of the whole process system. In the context of the national advocacy of "waste-free cities", environmental protection is accelerated on the agenda, with Internet-based hazardous waste intelligent environmental protection construction management patterns making an initial appearance [37]. Therefore, oil and gas extraction enterprises should further strengthen the life-cycle of intelligent hazardous waste environmental management, strengthen the assessment of the hazardous waste management capacity of oil and gas enterprises, continue to establish a sound hazardous waste regulatory system, and actively build a hazardous waste information control platform. From the perspective of life-cycle management, it is important to improve the information system of hazardous waste environmental management, realize smooth networking connection and real-time interaction with the national hazardous waste environmental management information system, and implement integrated intelligent monitoring in key hazardous waste supervision units to realize the tracking of hazardous waste information in the whole process to further enhance the level of data application and risk warning.

5. Conclusions

This paper analyzed the elements of hazardous waste management in oil and gas enterprises. Through the management elements in relevant policies and the indicators in the research literature related to the improvement of the management ability of oil and gas enterprises, combined with the concept of life-cycle management, an evaluation index system for the management ability of hazardous waste in oil and gas enterprises was constructed, with the aim to help oil and gas enterprises improve the level of hazardous waste management.

The potential impact of economic and technical factors should be considered more carefully in future research, and the main technical and economic indicators of hazardous waste disposal projects should be further explored. In future work, field investigation may be important. Future research can more comprehensively investigate the situation by combining the actual situation of a company, and constantly revising the evaluation index system according to the actual situation, so that the index system can be more applicable in real environments. We will cooperate with enterprises to collect relevant data and urge them to adhere to the principle of the "reduction, resourcefulness and harmlessness" of hazardous waste disposal in the process of oil and gas resources development so as to help the ecological construction of civilization from the perspective of sustainable development.

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