INTRODUCTION

Oil and gas resources are an important energy base for modern human society to survive and therefore known as the “blood” of industry. Faced with the difficult situation of oil and gas resources exploitation, resource depletion, and serious environmental pollution, human beings need to rethink the industrial development model and industrial process. It is necessary for human beings to examine the relationship among industrial development and economic, social, technological, resource, and environment from a new perspective. The eco-industrial park (EIP) located in the oil and gas resource-based city, due to its special mode of production and management activities, faces more severe environmental pressure than other EIPs do, and its resource depletion is particularly prominent. Establishing an ecological industry in oil and gas resource-based cities is more difficult because the key issue is to ensure the stability of oil exploration while vigorously developing the oil-edge industries, such as petrochemical and fine chemicals, petroleum equipment manufacturing, new chemical materials and other key industrial clusters, and other emerging industries. There has been a very important progress in the theoretical and practical research of EIPs in the world. Cote and Hall\(^1\) believes that EIPs are based...
on theoretical research and practical analysis of more than a dozen fields in the past decade. Lowe et al² proposed that the EIP is a corporate community consisting of manufacturing and service industries that try to improve environmental and economic benefits through cooperation in environmental resource management such as energy, water, and materials. Gibbs and Deutz pointed out that the formation of the concept of EIP mainly comes from industrial ecology. The establishment of EIP based on the relevant principles of industrial ecology can better realize the sustainable development of industrialized society. North and Giannini-Spohn⁴ examined the development policies and experiences of 60 EIPs in the Netherlands, and concluded that EIPs were formed under the combined effect of two aspects. One is the differentiation of location markets due to the high side of the location trend and the other is because the government has issued the new concepts resulting from environmental and economic research. The main difference between oil and gas resource-based urban EIPs and other EIPs is this industrial park relies on oil and gas resources, facing the challenge of environmental pressures, and resource depletion. It is necessary to evaluate the ecological efficiency of industrial park networks, understand the level of ecological efficiency, and reduce the energy use by the park. It is also important to increase the intensity of resource use and the efficiency of the use of renewable resources so as to reach a level consistent with ecological carrying.

Based on the developmental direction and characteristics of oil and gas resource-based cities, this paper provides the definition of oil and gas resource-based urban EIP. That is the petrochemical industry-led park in the oil and gas resource-based city consisting of a variety of ecological industries. Through the sharing of information, water, energy, infrastructure, and other resources within the park, the new form of industrial system organization is to maximize the environmental and economic benefits, reduce the depletion of oil and gas resources, and ultimately achieve the greater benefit for the community as opposed to each individual industry.

1.1 The meaning of industrial coupling symbiotic network

“Network” refers to a system of connected individuals. “Symbiosis” is a concept in the field of biology that mainly refers to various types of relationships between two different and interacting species. “Coupling relationship” refers to the relationship between two things that interact and influence each other. Researchers have focused their studies on the industrial symbiosis network and believed that the industrial symbiosis network refers to the long-term regional and industrial formation of cooperative symbiotic relationship. This relationship is through the exchange of materials, energy, knowledge, human resources, and technical resources for the purpose of obtaining environmental benefits and competitive advantages. The relationship between various eco-industrial enterprises in an EIP is called “industrial coupling symbiosis.” The industrial coupling symbiosis network in a park constitutes a high-efficiency closed-loop system. The system emphasizes the cooperation among various eco-industrial enterprises, thereby realizing the effective utilization, rational allocation, environmental protection, and efficiency improvement of resources in the park. This paper believes that the network not only refers to the exchanges between different enterprises, but also the mutual promotion between different enterprises through the mutually beneficial coupling relationship. There have been a lot of research on coupling and symbiosis in the EIPs. Wedekind et al⁵ studied the issues of construction, operation, and security of the EIPs. Lydia⁶ proposed that the EIPs is a closed-loop-cycle system, which is compromised by a variety of organizations working together for the construction and development of the park. Mirata⁷ studied the EIPs and the industrial ecological systems consisting of industrial coupling and symbiosis networks. Olli⁸ defined the concept of industrial symbiosis (IS) networks and discussed the symbiosis efficiency through case analysis. Côté (1998) argued that promoting the diversity and redundancy of the eco-industrial chains in industrial symbiosis system would improve the stability of the system. Lowitt⁹ found that economic measures, information, and financing are the critical factors influencing the symbiosis stability of the EIPs. Fleig¹² studied the risks of the industrial symbiosis network in EIPs. He believed that the more companies are dependent on each other: the less stable the symbiosis network is and the higher is the risk coefficient. Majumdar¹³ analyzed the key factors influencing the stability of the industrial symbiosis network in the EIPs. Ma et al¹⁴ indicated that there are three levels of the coupling in the EIPs: internal-business coupling, inter-business coupling, and business-regional coupling relationships. Qi et al¹⁵ discussed the connotation of the coupling of eco-industrial chain, and summarized current researches based on different research methods. Huang¹⁶ studied the contribution rate of the coupling and symbiosis of the EIPs to the carbon emission reduction and proposed the coupling and symbiosis relationships among businesses. Wang et al¹⁷ studied the present status of coupling and symbiosis relationships of the automotive eco-industrial chain in Xi’an High Tech Industries Development Zone of China. He proposed an effective mechanism to facilitate the establishment of the coupling and symbiosis relationships. Based on the previous research and analysis on the coupling and symbiosis theories, this article proposes the definition of ICSN. That is, it is an advanced chain network system, an eco-industrial chain network of “Producer-Consumer-Disintegrators” within its members and environment. The companies in the network facilitate and benefit each other
so that it realize full employment of the materials, energy, appreciation of total resources, and ultimately, sustainable development.

1.2 | The meaning of eco-efficiency of industrial coupling symbiotic network

The concept of eco-efficiency was originally proposed by the Canadian Scientific Council (SCC) in the 1970s. In the 1980s, the International Union for Conservation of Nature and Natural Resources (IUCN) introduced ecological efficiency into the strategy of global conservation. In 1992, Swiss scholars, Schaltegger and Sturm, provided the definition of ecological efficiency. Later 1990s, different organizations and scholars in the world started to study the ecological efficiency, and offered the definitions of ecological efficiency. The most influential definition eco-efficiency is the one given by the World’s Sustainable Development of Industrial and Commercial Enterprises Commission (WBCSD) in 1995. The focal point of eco-efficiency is to reduce the intensity of resources and energy use, increase the efficiency of using renewable resources, enhance the recovery of substances, and reduce the emission of toxic substances. The Organization for Economic Co-operation and Development pointed out in 1998 that eco-efficiency refers to “the efficiency of ecological resources in the process of meeting the needs of human beings.” It can be expressed by the ratio of “output” and “input.” “Input” refers to the pressure on the environment caused by the production activities of a company while “output” refers to the sum of the value of products and services provided by the company, industry or economy. The eco-efficiency concept developed by the WBCSD and OECD offers a framework that is flexible enough to be widely applied and easily interpreted across a variety of industries, while providing a common set of indicators. Eco-efficiency is defined as (Verfaillie and Bidwell, 2000):

\[
\text{Eco-efficiency} = \frac{\text{Output}}{\text{input}} = \frac{\text{Productor service}}{\text{Environmental influence}}
\]

The eco-efficiency concept has been applied to various products and processes. In addition to products and processes, the eco-efficiency concept and indicators have also been applied to the design of industrial parks using process re-engineering. The eco-efficiency of single industries or groups of industries in particular industrial complexes has been evaluated, and the eco-efficiency of industrial symbiosis network has also been assessed. Park and Behera provided an eco-efficiency evaluation formula for industrial symbiosis networks, \( \text{ECO-efficiency} = \frac{\sum EI}{ENm} \), where EI is the output indicator and economic benefit; ENm is the input indicator, environmental impact (resource consumption, energy consumption, CO2). This paper is based on the WBCSD approach and Park and Behera’s evaluation method to define the meaning of the eco-efficiency of the industrial coupling symbiosis network. The eco-efficiency of the industrial coupling symbiosis network is the ratio of the output of the network to the input of the network, reflecting the development level of the industrial coupling symbiosis network of the EIP. The formula is:

\[
\text{ICSN Ecological Efficiency} = \frac{\text{Symbiotic Output}}{\text{Symbiotic Input}},
\]

where symbiotic input represents the ecological impact and resource intensity of the industrial coupling symbiotic network in operation, and symbiotic output represents the value of products and services the network produced and the combined effects of industrial coupling and symbiosis.

The industrial coupling symbiotic network of oil and gas resource-based urban EIPs faces various risks and unstable factors in its operation process. It needs to coordinate various factors such as economy, environment, and society into the development of an entire park. Therefore, it is necessary to understand and analyze the ecological efficiency level of the network. Therefore, this paper takes the industrial coupling symbiotic network of oil and gas resource-based urban EIP as the research focus, and uses the grey relational analysis method to evaluate the ecological efficiency level of the network.

2 | EVALUATION INDEX SYSTEM AND EVALUATION METHOD

2.1 | Establishment of evaluation index system

The eco-efficiency evaluation index of EIP industrial coupling symbiosis network is selected based on the evaluation indicators recommended in China's “Comprehensive Eco-industrial Park Standards.” When combined the definition of WBCSD’s eco-efficiency, and the indicators of Park and Behera's eco-efficiency evaluation with the discussion of the previous paragraph, it defines the meaning of the eco-efficiency of the industrial coupling symbiosis network. The economic benefit index is the output index, while the environmental benefit impact and the material reduction cycle are the input indicators, and the material reduction cycle indicators include resource consumption and energy consumption. China’s oil and gas resource-based urban EIPs are mostly built around the petrochemical industry. In this network structure, the core enterprises are the creators of the network. Once the operating environment of the core enterprises changes, the satellite enterprises will be strongly impacted. Therefore, it is expected that the stability of this type of industry-coupled symbiotic network is not strong enough. The units in the coupled symbiotic
network system need to maintain close contact, and strengthen the network through the replacement of resources, energy, products, and waste. The linkage of the enterprise to ensure its stable operation can improve the eco-efficiency of this coupled symbiotic network model. This is the characteristic that the evaluation of industrial coupling symbiosis network is different from evaluating other objects. Therefore, when designing the indicator system, the structural indicators of a network was added as an input indicator. When combining the characteristics of oil and gas resources-based urban EIPs with economic benefits as the main driving force and the connotation of ecological efficiency, energy consumption, and environmental loss, the study generated 19 indicators at the four levels of benefit impacts, economic, environmental, material reduction cycle, and network structure. The evaluation index system is shown in Table 1.

In order to evaluate the eco-efficiency of the EIPs, we would like to take both of the features of the network and the influential factors of the evaluation into consideration. Through the exchanges of materials, products, and connections among the units in the coupling and symbiosis network, it will lower the cost of sharing technologies and faster delivering information. It will be helpful to enact business strategies, hold conference or seminars, human resource exchange, employee training, and other visible knowledge delivery. This paper takes the rate of enterprise link, the level of technology development link, the degree of enterprise information sharing, the degree of industrial diversity contribution, and the rate of material exchange as the five network structure indicators of the eco-efficiency of the ICSN of the EIPs. 30,31

### 2.2 Evaluation method

There are many ways to evaluate the ecological efficiency, such as the Ecological Footprint model, Ecological Carrying Index Model, State Space Model, Three-Dimensional State Space Model. Grey correlation analysis uses the degree of geometric similarity of sequence curve to determine whether the connection is tight. The more similar the geometric curve is, the higher the corresponding correlation degree is. The closer to the target value, the better the evaluation object with the

| Categories | Indicators | Specific indicators | Unit |
|------------|------------|---------------------|------|
| Output index | Economic performance B1 | Industrial added value growth rate | % |
| | | Per capita industrial added value | Million yuan/person |
| | | “Three wastes” comprehensive utilization of product output value | Million yuan |
| | | Per capita annual income of workers | Million yuan |
| Input index | Environmental benefit B2 | Solid waste discharge of Unit industrial output value | kg/Million yuan |
| | | Concentration of municipal wastewater treatment | % |
| | | Average annual concentration of TSP in the park network | pg/m³ |
| | | Average annual concentration of SO₂ in the park network | pg/m³ |
| | | Average annual concentration of NO₂ in the park network | pg/m³ |
| Substance reduction cycle B3 | Unit industrial added value comprehensive material consumption | Ton standard coal/Million yuan |
| | Comprehensive energy consumption of unit oil and gas production | Kilotogram standard coal/ton |
| | Unit industry added value fresh water consumption | m³/Million yuan |
| | Utilization ratio of industrial solid waste disposal | % |
| | Resource output rate | % |
| | Enterprise link rate in the park network | % |
| | Material exchange utilization | % |
| | Enterprise information sharing in the network | % |
| | Investment level of enterprise development link technology | Million yuan |
| | Contribution degree of industrial diversity | % |
highest degree of grey correlation. Since the eco-efficiency system of the coupled symbiotic network of the oil and gas resource-based urban EIP has obvious structural ambiguity, it is necessary to make a correlation analysis of factors in order to achieve less input and more output, economic, environmental, and other benefits. Therefore, the grey correlation method is applicable to the comparative evaluation of the industrial park coupling symbiotic network of ecological parks. The degree of correlation is used to comprehensively analyze and evaluate the level of ecological efficiency of the objects, and sort them to find out the main factors affecting the ecological efficiency. The key is to determine the optimal sequence of evaluation. The column of reference data is usually the best level of each indicator of the ICSN of several EIPs. It is actually the “ideal model” of the existing ICSN in a specific region. This model is the criterion for the evaluation of relevance, and then it is evaluated by comparing the symbiotic networks of various industries with this model. The advantage of this method is that there is no excessive requirement for sample capacity, which can fully reflect the changing trend of a certain indicator, and can indicate the importance of the indicator. When the decision makers form the strategy, they can make it from a macro-based point of view. Therefore, this paper selects grey correlation analysis to evaluate the ICSN of oil and gas resource-based urban EIP. The evaluation steps are as follows:

2.2.1 Selection of reference columns

Setting: \( i \) is the serial number of the \( i \) evaluation unit, \( i = 1, 2, \ldots, m \), \( k \) is the serial number of the \( k \) evaluation index of the index level, \( k = 1, 2, \ldots, n \), and \( V_{ik} \) is the value of the \( k \) index of the \( i \) evaluation unit. The best value \( x_{0k} \) of each index is taken as the entity of the reference sequence \( x_0 \). So there are

\[
x = (x_{01}, x_{02}, \ldots, x_{0n})
\]

\( x_{0k} = \text{optimum}(x_{ik}), i = 1, 2, \ldots, m; k = 1, 2, \ldots, n; \) (2)

2.2.2 Normalization of index value

In order to compare the indexes, we need to standardize the index values.

For positive indicators, the following formulas are used for normalization,

\[
X_{ik} = \frac{V_{ik} - \min_i V_{ik}}{\max_i V_{ik} - \min_i V_{ik}}.
\]

For reverse indicators, the following formulas are used for normalization,

\[
X_{ik} = \frac{\max_i V_{ik} - V_{ik}}{\max_i V_{ik} - \min_i V_{ik}}.
\]

After standardizing the treatment,

\[
X = (X_{ik})_{m \times n} = \begin{bmatrix}
X_{11} & X_{12} & \cdots & X_{1n} \\
X_{21} & X_{22} & \cdots & X_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{bmatrix}
\]

2.2.3 Determine the weights corresponding to the values of each index

Analytic hierarchy process and other index-weight-determination methods can be used to determine the priority weights of index level relative to the upper level indicators,

\[
w = (w_1, w_2, \ldots, w_n)
\]

In the form, \( \sum_{i=1}^{n} w_i = 1. \) (7)

2.2.4 Calculation of correlation coefficient

The normalized number column \( X_i = (X_{i1}, X_{i2}, \ldots, X_{in}) (i = 1, 2, \ldots, n) \) is used as a reference sequence, the formula for calculating the correlation coefficient is as follows:

\[
\sigma_{ik} = \frac{\min_i |X_{0k} - X_{ik}| + \rho \max_i |X_{0k} - X_{ik}|}{|X_{0k} - X_{ik}| + \rho \max_i |X_{0k} - X_{ik}|},
\]

\( i = 1, 2, \ldots, m; k = 1, 2, \ldots, n; \) The \( \rho \) in the formula is the resolution coefficient, \( \rho \in [0, 1] \). Usually take \( \sigma = 0.5 \).

Calculation of correlation coefficient by formula \( \xi_{ik} (i = 1, 2, \ldots, m; k = 1, 2, \ldots, n) \), the following correlation coefficient matrix is obtained:

\[
E = (\xi_{ik})_{m \times n} = \begin{bmatrix}
\xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\
\xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\xi_{m1} & \xi_{m2} & \cdots & \xi_{mn}
\end{bmatrix}
\]

In the form, \( \xi_{ik} \) as the correlation coefficient of the \( i \) evaluation unit \( k \) index and the \( k \) best indicator.

2.2.5 Calculation of grey weighted correlation degree

The calculation formula of the degree of grey correlation is

\[
R = (r_1)_{1 \times m} = (r_1, r_2, \ldots, r_m) = WE^T.
\]

2.2.6 Evaluation and analysis of ecological efficiency of the ICSN

According to the size of the grey weighted association, the evaluation objects are sorted, that is, the correlation order of
the evaluation objects is established. The greater the degree of relevance, the higher the eco-efficiency level of the ICSN in the park.46

3  | THE EVALUATION OF THE ECO-EFFICIENCY OF THE ICSN IN DAQING ECO-INDUSTRIAL PARK A

3.1  | The subject evaluated

Since its establishment in 2004, Daqing A EIP has formed a strongly comprehensive park, including natural, industrial, and social new forms of organization. It has formed its own characteristics in product metabolism and waste metabolism. The embryonic form of the eco-industry has emerged in the continuous breakthrough of informationization. In 2011, the former Honggang District Iron Man Park and the original Qingnan Industrial Park carried out industrial upgrading and merged with Xinglong Building Materials Equipment Industrial Park to form a new Daqing A EIP. The Daqing A Industrial Park consists of three parks with a total planned area of 55.1 square kilometers and a total of 97 enterprises.

Eco-Industrial Park A in Daqing City has already formed as relying on industry-coupled symbiotic network based on six industry chains. That is to take the natural gas processing industry and petrochemical refined products, with the projects of photovoltaic power generation industry, smart greenhouse industry, bulk logistics industry, and building materials industry as satellites. There are techno-economic relationships among the industry chains with the inputs and outputs as connections. It demonstrates natural coupling relationship and comes with strong scale advantages. By 2017, it has achieved the goal of 10 billion yuan in output value, 1 billion yuan in profits and taxes, and more than 8000 jobs.

3.2  | Data analysis

This paper mainly collects the data of Daqing A EIP from 2011 to 2016 by questionnaire survey and field visit. The survey object is the campus management personnel, and the original values of the evaluation indicators are shown in Table 2.

For C5, C7, C8, C9, C10, C11, C12, and other reverse evaluation indicators, we use the formula (4) for numerical standardization. For C1, C2, C3, C4, C6, C13, C14, C15, C16, C17, C18, C19, and other positive evaluation indicators, we use the formula (3) for numerical standardization processing. Finally, the standardized values of the raw data of each evaluation index are shown in Table 3.

The analytic hierarchy process is used to determine the weight of each indicator. In order to obtain a quantitative judgment matrix, a judgment matrix is established by means of a questionnaire survey, and 2-4 experts in the park

| Index number | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | Optimal value |
|--------------|------|------|------|------|------|------|--------------|
| B1 C1        | 28.7 | 24.1 | 31.6 | 42.6 | 45.5 | 46.1 | 46.1         |
| C2           | 17.1 | 22.4 | 33.6 | 36.7 | 35.6 | 34.2 | 36.7         |
| C3           | 42   | 60   | 54   | 90   | 82   | 97   | 97           |
| C4           | 6    | 6.8  | 7    | 7.9  | 8.3  | 9    | 9            |
| B2 C5        | 36.29| 27.83| 28.15| 26.23| 20.31| 18.12| 18.12        |
| C6           | 53   | 69   | 66   | 72   | 69   | 80   | 80           |
| C7           | 85   | 94   | 78   | 72   | 70   | 66   | 66           |
| C8           | 65   | 76   | 56   | 50   | 46   | 42   | 42           |
| C9           | 43   | 51   | 33   | 29   | 29   | 31   | 29           |
| B3 C10       | 55.3 | 51.5 | 49.7 | 46.7 | 52.4 | 44.2 | 44.2         |
| C11          | 24.7 | 22.1 | 18.8 | 18.5 | 17.3 | 16.43| 16.43        |
| C12          | 9    | 9.2  | 8.4  | 9    | 7.8  | 6.5  | 6.5          |
| C13          | 86   | 89   | 90   | 86   | 90   | 92   | 92           |
| C14          | 44.5 | 37.3 | 41.5 | 55.7 | 57.1 | 61.5 | 61.5         |
| B4 C15       | 45   | 51   | 55   | 56   | 65   | 58   | 65           |
| C16          | 19   | 24   | 27   | 33   | 35   | 32   | 35           |
| C17          | 41   | 47   | 52   | 53   | 62   | 67   | 67           |
| C18          | 49   | 53   | 62   | 65   | 75   | 71   | 75           |
| C19          | 55   | 60   | 70   | 82   | 85   | 85   | 85           |
management personnel are selected to jointly evaluate the judgment matrix. Using the 1-9 scale method, the relative importance of the B-level indicators for the A-layer and C-level indicators for the B-layer is examined separately. Since the weight of the specific indicator layer relative to the level of eco-efficiency of the ICSN of the total target-level EIP is equal to the product of the first-level weight and the second-level weight, the weights of each layer can be calculated, as shown in Table 4.

The consistency checking process of the total hierarchy is as follows

\[ R_1 = [0.4133, 0.2922, 0.1867, 0.1077] \]
\[ = [0.583021, 0.601107, 0.706369] \]

\[ R_2 = [0.3805, 0.2883, 0.1104, 0.1104] \]
\[ = [0.542388, 0.604731, 0.670433, 0.750975, 0.79422, 0.907256] \]

\[ CI = 0.005, RI = 0.580, CR = \frac{CI}{RI} = 0.008 < 0.1. \]

Total hierarchical ordering passed the consistency test. Then, formula 8 is used to calculate the grey correlation coefficient of each index, for \( \sigma = 0.5 \), the calculation results are shown in Table 5.

Finally, the degree of grey correlation of the standard layer of economic benefit, environmental benefit, material reduction cycle, and network structure is calculated, respectively.

The grey correlation coefficient of economic benefit,

\[
\begin{bmatrix}
0.6124 & 0.5555 & 0.6547 & 0.8870 & 0.9786 & 1 \\
0.5838 & 0.6578 & 0.8986 & 1 & 0.9615 & 0.9166 \\
0.3333 & 0.4263 & 0.3900 & 0.7971 & 0.6470 & 1 \\
0.9016 & 0.9259 & 0.9322 & 0.9615 & 0.9751 & 1 \\
0.911169 & 0.911219 & 0.975531 & & & 
\end{bmatrix}
\]

The grey correlation coefficient of environmental benefits,

\[
\begin{bmatrix}
0.5349 & 0.6402 & 0.6355 & 0.6650 & 0.7761 & 0.8273 \\
0.4867 & 0.6790 & 0.6321 & 0.7333 & 0.6790 & 0.9322 \\
0.5913 & 0.4954 & 0.6962 & 0.8208 & 0.6790 & 1 \\
0.5445 & 0.4471 & 0.6626 & 0.7746 & 0.8730 & 1 \\
0.6626 & 0.5555 & 0.8730 & 1 & 1 & 0.9322 
\end{bmatrix}
\]

**TABLE 3** Standardized values of ICSN evaluation index in Daqing A EIPs

| Index number | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | Optimal value |
|--------------|-------|-------|-------|-------|-------|-------|---------------|
| B1 B2 C10    | 0.209091 | 0     | 0.340909 | 0.840909 | 0.972727 | 1     | 1             |
| B1 B2 C11    | 0     | 0.270408 | 0.841837 | 1     | 0.943878 | 0.872449 | 1             |
| B1 B2 C12    | 0     | 0.327273 | 0.218182 | 0.872727 | 0.727273 | 1     | 1             |
| B1 B2 C13    | 0     | 0.266667 | 0.333333 | 0.633333 | 0.766667 | 1     | 1             |
| B1 B2 C14    | 0     | 0.465603 | 0.447991 | 0.55366 | 0.879472 | 1     | 1             |
| B1 B2 C15    | 0     | 0.592593 | 0.481481 | 0.703704 | 0.592593 | 1     | 1             |
| B1 B2 C16    | 0.321429 | 0     | 0.571429 | 0.785714 | 0.857143 | 1     | 1             |
| B1 B2 C17    | 0.323529 | 0     | 0.588235 | 0.764706 | 0.882353 | 1     | 1             |
| B1 B2 C18    | 0.363636 | 0     | 0.818182 | 1     | 1     | 0.909091 | 1             |
| B1 B2 C19    | 0     | 0.342342 | 0.504505 | 0.774775 | 0.261261 | 1     | 1             |
| B1 B2 C20    | 0     | 0.314389 | 0.713422 | 0.749698 | 0.8948 | 1     | 1             |
| B1 B2 C21    | 0.074074 | 0     | 0.296296 | 0.074074 | 0.518519 | 1     | 1             |
| B1 B2 C22    | 0     | 0.5     | 0.666667 | 0     | 0.666667 | 1     | 1             |
| B1 B2 C23    | 0.297521 | 0     | 0.173554 | 0.760331 | 0.818182 | 1     | 1             |
| B1 B2 C24    | 0     | 0.3     | 0.5     | 0.55 | 1     | 0.65 | 1             |
| B1 B2 C25    | 0     | 0.3125 | 0.5     | 0.875 | 1     | 0.8125 | 1             |
| B1 B2 C26    | 0     | 0.230769 | 0.423077 | 0.461538 | 0.807692 | 1     | 1             |
| B1 B2 C27    | 0     | 0.153846 | 0.5     | 0.615385 | 1     | 0.846154 | 1             |
| B1 B2 C28    | 0     | 0.166667 | 0.5     | 0.9 | 1     | 1   | 1             |
| Index                             | First level weight | Specific indicators | Two level weight | Total weight |
|----------------------------------|--------------------|---------------------|------------------|--------------|
| Economic performance B1         | 0.4203             | C1                  | 0.4133           | 0.1737100    |
|                                  |                    | C2                  | 0.2922           | 0.1228117    |
|                                  |                    | C3                  | 0.1867           | 0.0784700    |
|                                  |                    | C4                  | 0.1077           | 0.0452663    |
| Environmental benefit B2        | 0.2685             | C5                  | 0.3805           | 0.1021643    |
|                                  |                    | C6                  | 0.2883           | 0.0774086    |
|                                  |                    | C7                  | 0.1104           | 0.0296424    |
|                                  |                    | C8                  | 0.1104           | 0.0296424    |
|                                  |                    | C9                  | 0.1104           | 0.0296424    |
| Substance reduction cycle B3     | 0.1899             | C10                 | 0.3543           | 0.0672816    |
|                                  |                    | C11                 | 0.2685           | 0.0509882    |
|                                  |                    | C12                 | 0.1877           | 0.0356442    |
|                                  |                    | C13                 | 0.1115           | 0.0211739    |
|                                  |                    | C14                 | 0.0779           | 0.0147932    |
| Network structure B4             | 0.1213             | C15                 | 0.4084           | 0.0495389    |
|                                  |                    | C16                 | 0.2694           | 0.0326782    |
|                                  |                    | C17                 | 0.1511           | 0.0183284    |
|                                  |                    | C18                 | 0.0997           | 0.0120936    |
|                                  |                    | C19                 | 0.0713           | 0.0086487    |

**TABLE 4** Index weight of ecological efficiency evaluation of ICSN in EIPs

| Index | 2011   | 2012   | 2013   | 2014   | 2015   | 2016 |
|-------|--------|--------|--------|--------|--------|------|
| C1    | 0.6124 | 0.5555 | 0.6547 | 0.8870 | 0.9786 | 1    |
| C2    | 0.5838 | 0.6578 | 0.8986 | 1      | 0.9615 | 0.9166|
| C3    | 0.3333 | 0.4263 | 0.3900 | 0.7971 | 0.6470 | 1    |
| C4    | 0.9016 | 0.9259 | 0.9322 | 0.9615 | 0.9751 | 1    |
| C5    | 0.5349 | 0.6402 | 0.6355 | 0.6650 | 0.7761 | 0.8273|
| C6    | 0.4867 | 0.6790 | 0.6321 | 0.7333 | 0.6790 | 0.9322|
| C7    | 0.5913 | 0.4954 | 0.6962 | 0.8208 | 0.873  | 1    |
| C8    | 0.5445 | 0.4471 | 0.6626 | 0.7746 | 0.8730 | 1    |
| C9    | 0.6626 | 0.5555 | 0.8730 | 1      | 1      | 0.9322|
| C10   | 0.7124 | 0.7902 | 0.8333 | 0.9166 | 0.7703 | 1    |
| C11   | 0.7688 | 0.8290 | 0.9206 | 0.9299 | 0.9693 | 1    |
| C12   | 0.8986 | 0.8928 | 0.9166 | 0.8986 | 0.9353 | 0.9786|
| C13   | 0.8730 | 0.9649 | 1      | 0.8730 | 1      | 0.9322|
| C14   | 0.6179 | 0.5319 | 0.5789 | 0.8258 | 0.8620 | 1    |
| C15   | 0.5789 | 0.6626 | 0.7333 | 0.7534 | 1      | 0.7971|
| C16   | 0.6179 | 0.6962 | 0.7534 | 0.9016 | 0.9649 | 0.8730|
| C17   | 0.5140 | 0.5789 | 0.6470 | 0.6626 | 0.8461 | 1    |
| C18   | 0.5140 | 0.5555 | 0.6790 | 0.7333 | 1      | 0.87301|
| C19   | 0.4782 | 0.5238 | 0.6470 | 0.9016 | 1      | 1    |

**TABLE 5** Grey relational degree coefficient matrix table
The grey correlation coefficient of material reduction cycle:

\[
R_3 = \begin{bmatrix}
0.3543 & 0.2685 & 0.1877 & 0.1115 & 0.0779 \\
0.7124 & 0.7902 & 0.8333 & 0.9166 & 0.7703 \\
0.7688 & 0.8290 & 0.9206 & 0.9299 & 0.9693
\end{bmatrix} \times \begin{bmatrix}
0.8986 & 0.8928 & 0.9166 & 0.8986 & 0.9353 \\
0.8730 & 0.9649 & 1 & 0.8730 & 1 \\
0.6179 & 0.5319 & 0.5789 & 0.8258 & 0.8620
\end{bmatrix}
\]

\[
= \begin{bmatrix}
0.772967 & 0.819154 & 0.871061 & 0.904766 & 0.88738 \\
0.5789 & 0.6626 & 0.7333 & 0.7534 & 1 \\
0.6179 & 0.6962 & 0.7534 & 0.6626 & 0.8461 \\
0.5140 & 0.5789 & 0.6470 & 0.6626 & 0.8461 \\
0.4782 & 0.5238 & 0.6470 & 0.9016 & 1
\end{bmatrix}
\]

\[
R_4 = \begin{bmatrix}
0.4084 & 0.2694 & 0.1511 & 0.0997 & 0.0713 \\
0.583021 & 0.601107 & 0.706369 & 0.911169 & 0.911219 \\
0.542388 & 0.604731 & 0.670433 & 0.750975 & 0.79422 \\
0.772967 & 0.819154 & 0.871061 & 0.904766 & 0.96719 \\
0.565892 & 0.638364 & 0.714035 & 0.788093 & 0.975531
\end{bmatrix}
\]

\[
= \begin{bmatrix}
0.565892 & 0.638364 & 0.714035 & 0.788093 & 0.96719 \\
0.6063 & 0.6482 & 0.7291 & 0.8522 & 0.8823 \\
0.4203 & 0.2685 & 0.1899 & 0.1213 & 0.2685
\end{bmatrix}
\]

The grey correlation coefficient of network structure:

At the same time,

\[
W_0 = \begin{bmatrix}
0.4203 & 0.2685 & 0.1899 & 0.1213
\end{bmatrix}
\]

Have

\[
E_T^T = \begin{bmatrix}
0.583021 & 0.601107 & 0.706369 & 0.911169 & 0.911219 & 0.975531 \\
0.542388 & 0.604731 & 0.670433 & 0.750975 & 0.79422 & 0.907256 \\
0.772967 & 0.819154 & 0.871061 & 0.904766 & 0.88738 & 0.988324 \\
0.565892 & 0.638364 & 0.714035 & 0.788093 & 0.96719 & 0.870161
\end{bmatrix}
\]

\[
R_0 = \begin{bmatrix}
0.4203 & 0.2685 & 0.1899 & 0.1213 \\
0.583021 & 0.601107 & 0.706369 & 0.911169 & 0.911219 & 0.975531 \\
0.542388 & 0.604731 & 0.670433 & 0.750975 & 0.79422 & 0.907256 \\
0.772967 & 0.819154 & 0.871061 & 0.904766 & 0.88738 & 0.988324 \\
0.565892 & 0.638364 & 0.714035 & 0.788093 & 0.96719 & 0.870161
\end{bmatrix}
\]

3.3 | The final analysis

According to the calculation of comprehensive annual ecological efficiency shown in Table 5, 2016 is the best year for the ecological efficiency of this EIP while 2011 is the least efficient year. From 0.6063 in 2011 to 0.9471 in 2016, the degree of correlation growth is 0.3408. Notably from 2013 to 2014, the EIP was the fastest growing year, with a growth of correlation of 0.1311. The grey correlation of economic benefits in 2014 is higher than the overall grey correlation, indicating that the economic benefits of the park are better during the year, which has led to the improvement of the overall level of ecological efficiency of the park. The overall eco-efficiency curve and environmental benefit curve of the park are highly similar, indicating that the development trend of the two areas is basically consistent. When the environmental benefits increase, the overall eco-efficiency level of
the park naturally increases, but the environmental benefit curve has basically been in a low status. This indicates that in the process of building the park, we should pay attention to environmental protection and ecological governance. As the network structure indicator, which affects the industrial coupling symbiosis of the park, there has been a significant increase in 2014-2015, which has made up for the shortage due to the reduction of the park's economic efficiency and material cycle indicators to stimulate the park's ecology. It is worth mentioning that the material reduction cycle index of the park has always been higher than the overall eco-efficiency grey correlation, indicating that the park has been vigorous in improving the efficiency of resource and energy use and promoting the circular development of the park.

4 | ECO-EFFICIENCY EVALUATION OF INDUSTRIAL COUPLING SYMBIOTIC NETWORK OF DIFFERENT OIL AND GAS RESOURCES URBAN ECO-INDUSTRIAL PARKS

4.1 | Data processing

In order to better understand the development of oil and gas resource-based urban EIPs, this paper also selected the EIPs of four different oil and gas resource-based cities in Daqing, Panjin, Karamay, and Dongying for the horizontal comparison. The data selected shown in Table 7 is the mean of the four parks from 2015 to 2016.

The ecological efficiency evaluation of the industrial coupling symbiotic network of four oil and gas resource-based urban EIPs are calculated by using the analytic hierarchy process and the grey relational analysis method, as shown in Table 8.

4.2 | Analysis of results

The order of the eco-efficiency levels of the four parks are Daqing > Dongying > Karamay > Panjin, and the order of economic benefits is Daqing > Karamay > Dongying > Panjin. The order of environmental benefits is Panjin > Daqing > Karamay > Dongying. The order of material reduction and circulation is Panjin > Dongying > Karamay > Daqing. The order of network structure is Daqing > Dongying > Karamay > Panjin. From this data, we can understand the development level of four different oil and gas resource-based cities. Daqing EIP leads the other three industrial parks in terms of economic benefits and park industry coupling symbiotic network construction, while Panjin has better environmental benefits, but overall ecological efficiency is low along with its grey correlation of the other three indicator layers being low. While Karamay and Dongying pay more attention to the balanced development of economic benefits, environmental benefits, material recycling, and network structure.

5 | CONCLUSION AND SUGGESTIONS

Through this evaluation of eco-efficiency of the ICSN of the EIPs in oil and gas resource cities, we have reached the following conclusions.

1. From 2011 to 2016, the eco-efficiency grey correlation of the ICSN of Daqing EIP is increasing, indicating that the Daqing EIP is continuously extending the eco-industrial chain and improving the industrial symbiosis network of the park. The aspect has achieved remarkable results.

2. Based on the “Comprehensive Eco-industrial Park Standards,” this paper analyzes the economic, environmental, and material-reduction-circular impact indicators measuring the impact of the ecological efficiency of EIPs combining with the characteristics of oil and gas resource-based urban EIPs. According to the relevant theory of industrial ecology, we added the network structure impact index and we constructed the eco-efficiency evaluation index system of the ICSN of oil and gas resource-based urban EIP. The index system can comprehensively reflect the efficiency level and long-term trend of the ICSN development.

3. We evaluated the eco-efficiency of the industrial coupling co-existing network of different oil and gas resource-based urban EIPs in different years and in
different oil and gas resource-based urban EIPs. Our research is different from the other research on the weights and correlations of the indicators. We use the tomographic analysis method to assign the index weights, which is convenient to determine the impact of the indicators on evaluating the subject’s ecological efficiency, and uses the grey evaluation system to evaluate the trend of efficiency of the subject’s ecology. The results show that the comprehensive evaluation system combined with chromatographic analysis and grey correlation analysis can not only evaluate the overall ecological efficiency of the object, but also reveal the degree of correlation between the evaluation indicators and reflect the overall trend.

4. The limitation of this study is that the ecological efficiency of the ICSN of the oil and gas resource-based urban EIP was evaluated using only one method, grey correlation analysis method. It provides us no choice of multiple methods for comparative evaluation. The authors will continue to research on this issue by finding multiple methods for comparative evaluation, and analyzing the evaluation result to ensure the accuracy of the evaluation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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