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Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks

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ABSTRACT

The benefit evaluation of industrial symbiosis in industrial parks plays an important part in park management. This study aims to propose a comprehensive assessment method for industrial symbiosis benefits by combining resource productivity and considering the impact of emissions in emergy analysis. Besides, classify industrial symbiosis according to the exchange of materials, water, and energy to conduct an in-depth analysis of diverse symbiosis. The case study of an eco-industrial park in China shows that industrial symbiosis has a positive effect in many aspects, including increasing the productivity of direct input materials, water, and energy by 0.33, 36.50, and 0.38 times respectively, reducing the emission impact by 30.91%, saving economic investment equal to 30.18% of gross domestic product, reducing the environmental load rate by 23.88% and increasing the sustainable development index by 32.74%. Suggestions on building a symbiosis network are put forward by comparing the contributions of symbiosis types. This study provides park managers with a symbiosis classification and a benefit evaluation tool to build symbiosis networks and make policies for sustainable industrial development.

1. Introduction

Industrial parks as part of local economic development strategies, have become the carrier of industrial development, with more than 20,000 in the world (Fuentes Barrera et al., 2021). However, rapid industrialization has caused uncontrolled exploitation and utilization of natural resources, which harm nature and human health (Tang et al., 2020). Industrial symbiosis is part of the industrial ecology, which aims to promote collaboration between enterprises involving the physical exchange of materials, water, energy, and/or by-products by using neighboring geographical advantages (Chertow, 2000). "International Guidelines for Industrial Parks" has mentioned industrial symbiosis many times in the planning and design of the park (Organization, 2019). In the EU's sustainable industry policy and the Green Deal, industrial symbiosis is also an important part (Wadström et al., 2021). China has formulated many standard policies on circular economy and eco-industrial parks to promote the development of industrial symbiosis (Uusikartano et al., 2021). In addition, emergent economies such as Brazil (Sellitto et al., 2021) and South Korea (Kim et al., 2018) have also advocated the implementation of industrial symbiosis to reduce environmental impact and improve the viability and profitability of enterprises. Nowadays, industrial symbiosis is the main form of industrial parks that protect the environment, develop a circular economy, and improve sustainability (Ren et al., 2016). To promote the concept and accelerate the sustainable development of industrial parks, quantitatively evaluating its comprehensive performance for industrial parks is necessary.

In recent years, life cycle assessment has been widely used to quantify environmental benefits of the symbiosis type (Santana et al., 2019; Simona Marinelli et al., 2020), symbiosis process (Hildebrandt et al., 2018; Lee et al., 2020), and symbiosis network (Aissani et al., 2019; Kerdlap et al., 2020), analyzing the reduction of various environmental impacts during the life cycle (Mohammed et al., 2018). Carbon footprint that can convert different resources into carbon dioxide equivalents is used to calculate the carbon emission reduction potential of the symbiosis (Dong et al., 2014). Material flow analysis is used to measure the saving potential of the symbiote by comparing the energy and water flows in different models, revealing the impact of economic activities on the environmental load (Hu et al., 2020). Therein, life cycle assessment ignores the contribution of ecosystem goods and services, or natural capital (Maiolo et al., 2021; Ukidwe and Bakshi, 2007). Carbon footprint only reflects the impact of climate

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change from one perspective. Material flow analysis fails to distinguish quality differences among various materials due to their diverse properties.

Emergy analysis created by Odum is based on thermodynamics and systems ecology, combined with global biogeochemical cycles to objectively evaluate the contribution of natural resources (Ukidwe and Bakshi, 2007). It overcomes the obstacles of incomparability between different inputs and transforms different materials, energy, and services into a common unit, linking socioeconomic systems with natural ecosystems. Based on the transformed input flows, there is an emergy index system for evaluating the economic benefits, environmental impact, and sustainability of a system. As a method that can consider economic issues the same as the environmental subject, emergy analysis has been widely used to compare relevant indexes of different time scales (Xu et al., 2021; Zhang et al., 2009, 2016) or different technical levels (Corcelli et al., 2018; Yuan et al., 2011) to comprehensively assess the evolution of the economy and the environment. To evaluate the symbiosis benefits at the industrial park level, indicators of recycling (Wang et al., 2005), emergy saving (Geng et al., 2010), and economic performance (Geng et al., 2014) have been proposed.

However, the application of emergy analysis in industrial symbiosis has two limitations. First, the negative effects on the natural environment and human health mitigated by industrial symbiosis cannot be reflected. In the sustainability assessment of production or systems, referring to the evaluation framework of Eco-indicator 99, disability adjusted life years (DALY) and potentially disappeared fraction (PDF) are used to describe the loss of natural and human capital caused by emissions (Pan et al., 2016; Ukidwe and Bakshi, 2007). This part of emergy is regarded as an indirect input to be provided again to replace the loss and maintain the sustainability of the system. Second, the intensive research on symbiotic contribution is insufficient. On the one hand, because all inputs are superimposed in the index, the advantage that emergy analysis quantifies incomparable items, such as types of energy resources and products, and even labor services (Brown and Ulgiati, 2004) cannot be fully reflected. Resource productivity of the flow of materials, energy, and water within the system has become a national strategic policy concern to quantify the performance of the circular economy (Bleischwitz, 2010; De Pascale et al., 2021). This indicator reflects the consumption of direct input resources per unit of economic output (Fraccascia and Giannoccaro, 2020) and thus is applied to the calculation of the utilization efficiency of various resources in the park. On the other hand, most of these studies focused on the benefits of the entire industrial park or each exchange process, with less attention on the different symbiosis types. When teasing out symbiosis networks, symbiosis relationships are grouped into three categories - materials, water, energy - based on exchange substances (Kerdlap et al., 2020; Zhang et al., 2017). However, the fact that a symbiosis relationship can exchange more than two categories of resources - materials, water, and energy at the same time is ignored. For example, the exchanged water often simultaneously replaces the functions of energy and by-products (Mendez-Alva et al., 2021).

With such circumstances, this study aims to develop an evaluation approach that combines emergy analysis and resource productivity to quantify the environmental and economic benefits of industrial symbiosis in the park. The impact of pollutant emissions is included to improve the indicators, and resource productivity is introduced to enrich the method of contribution identification. The symbiosis relationships are divided to explore the characteristics of the contribution. This study tests the method through an eco-industrial park in China with a complex symbiosis network. The results help park managers effectively evaluate symbiosis and implement precise decisions, provide a reference for building a symbiosis network, and promote sustainable industrial development.

2. Methodology

2.1. Types of industrial symbiosis

In a symbiotic process, the previous process produces valuable output flows relying on exchanged resources - materials, water, and energy, as inputs to the next production unit. In order to explore the contribution characteristics of diverse symbiosis, this study divided industrial symbiosis into four types according to the exchange of materials, water, and energy between symbiosis units.

(1) Material symbiosis. Industrial parks promote the cooperation between symbiosis units by mimicking the “producer-consumer-decomposer” model of biological ecosystems, and use by-products or waste generated by upstream production units as raw materials for downstream production. It is divided into two modes: deep processing of products and remanufacturing or recycling of waste.
(2) Water symbiosis. Water use efficiency and water pollution in production have been focused by park managers. Therefore, water symbiosis is considered as a special type of material symbiosis in the symbiosis system. Based on the difference in water quality requirements of different production processes, water resources are reused to the maximum extent to achieve water saving purposes.
(3) Energy symbiosis. Not only does it require companies to improve energy efficiency, but also requires the park to optimize energy exchange networks in accordance with the overall supply-demand relationship. Mainly adopt the method of energy cascading and cogeneration to improve energy utilization efficiency.
(4) Synergistic symbiosis. In order to avoid omission or overlapping in classification, synergistic symbiosis is proposed in this study, that is, there are two or more categories among the exchanged materials, energy, and water in a symbiosis relationship. Including material-water symbiosis, material-energy symbiosis, water-energy symbiosis, and material-water-energy symbiosis.

2.2. Emergy analysis

Emergy is expressed as the available energy directly or indirectly put into operation to make a service or product. To facilitate the addition or comparison of different types of energy contributing to production, it takes the solar energy which is the primary source of all processes and cycles as a unified dimension of evaluation, and its unit is solar emjoules (sej) (Odum, 1996). It represents all the work done by the environment to sustain the system and produce a given output, including natural and artificial processes (Jiang et al., 2009). Renewable resources (sunlight, wind, rain, etc.) are taken into account as environmental contributors in the emergy calculation. In addition, Brown et al. (2012) extended the unit emergy value (UEV) on the basis of transformation, which is defined as the equivalent solar emergy required to generate a unit of output and is commonly measured in sej/J or sej/g. By multiplying the inputs and outputs by the corresponding UEV, the emergy of each product or service can be calculated.

Emergy analysis starts from the energy movement of the Earth's biosphere and calculates the geobiosphere emergy baseline by counting the contributions of solar, geothermal, and gravitational potential exergy to quantify incomparable items (Brown and Ulgiati, 2004). The baseline is closely related to the UEV, a prerequisite for UEV calculation. There are many baselines, and the most frequently used is 9.24E+24 sej/a (Odum, 1996), 15.83E+24 sej/a (Odum, H.T., Brown, M. T., Williams, S. B., 2000), and 12.00E+24 sej/a (Brown et al., 2016). In this study, the latest 12.00 E+24 sej/a baseline was adopted. To ensure the accuracy and rigor of the emergy calculation, the quoted UEV should be multiplied by the ratio of the new baseline to the prior baseline for correction (Brown and Ulgiati, 2016).

Based on the same unit, all inputs in the system can be distinguished between renewable and non-renewable inputs and between local and external inputs, providing a more complete accounting of social ecosystems through a series of emergy-based indicators. When applying emergy analysis to quantify the benefits of industrial symbiosis in industrial parks, reference scenarios are created for index comparison with existing symbiosis. In a scenario called non-industrial symbiosis, there is no production unit utilizing valuable waste or by-products from another unit in the system. In addition, it is recommended that four symbiosis scenarios in which only corresponding symbiosis relationships exist are created to analyze the benefit contribution of different symbiosis types by comparing the emergy results with non-industrial symbiosis.

2.2.1. *Emergy flows of the industrial park*

Emergy analysis considers all systems as energy flow networks. The different flows and main process sources are determined based on the park boundary, and the emergy system diagram (Fig. 1) is drawn with the energy system symbols proposed by Odum (1996). Emergy inputs are divided into three categories: (1) inputs received within the system, namely local renewable resources (R) and local non-renewable resources (N); (2) the purchased inputs (F), namely imported resources (F_N), labor (L), services (S), and waste disposal (W); and (3) the impacts of emissions (E_L), namely ecological services needed to dilute pollution and emergy loss caused by emissions. In addition, the substances, energy, water, and/or by-products involved in symbiosis in the park can replace some of the raw materials, and those replaced are recorded as W_R.

2.2.2. *Quantification of ecological services for dilution*

Because nature can purify itself when pollutants are discharged, the atmosphere and water bodies provide the services of dilution, desalination, or decomposition such that the concentration of pollutants can reach an acceptable range for the ecosystem. The company's emissions strictly comply with the corresponding pollution emission standards, but some emission concentrations are higher than the allowable range (Zhang et al., 2009). Therefore, to calculate the ecosystem's contributions to industrial activities, these ecological services should be considered.

First, the dilution emergy of the atmosphere is expressed by the kinetic energy of dilution air, and it can be calculated with equations (1) and (2) (Liu et al., 2011):

$$M_{air} = d \times \frac{W}{c} \tag{1}$$

$$R_{W,\ air} = N_{kinetic} \times Tr_{air} = \frac{1}{2} \times M_{air} \times v^2 \times Tr_{wind} \tag{2}$$

Here, M_{air} is the mass of dilution air needed; d is air density (1.23 kg/m^3), W is the annual emissions of a given pollutant, c is the acceptable concentration from agreed regulations (Table 1), $R_{W,\ air}$ is the emergy of ecological service from air, $N_{kinetic}$ is the kinetic energy of dilution air moved by the wind, Tr_{air} is assumed to be the transformity of wind, and v is local annual average wind speed.

Second, the dilution emergy of water bodies is the chemical energy of dilution water and can be calculated according to equations (3) and (4) (Liu et al., 2011):

$$M_{water} = d \times \frac{W}{c} - M_0 \tag{3}$$

$$R_{W,\ water} = N_{chem} \times Tr_{water,chem} = M_{water} \times G \times Tr_{water,chem} \tag{4}$$

Here, M_{water} is the mass of the diluted water needed, d is the water density (1.00E+03 kg/m^3), M_0 is the mass of discharged water from the industrial park, $R_{W,\ water}$ is the emergy of ecological service from water,

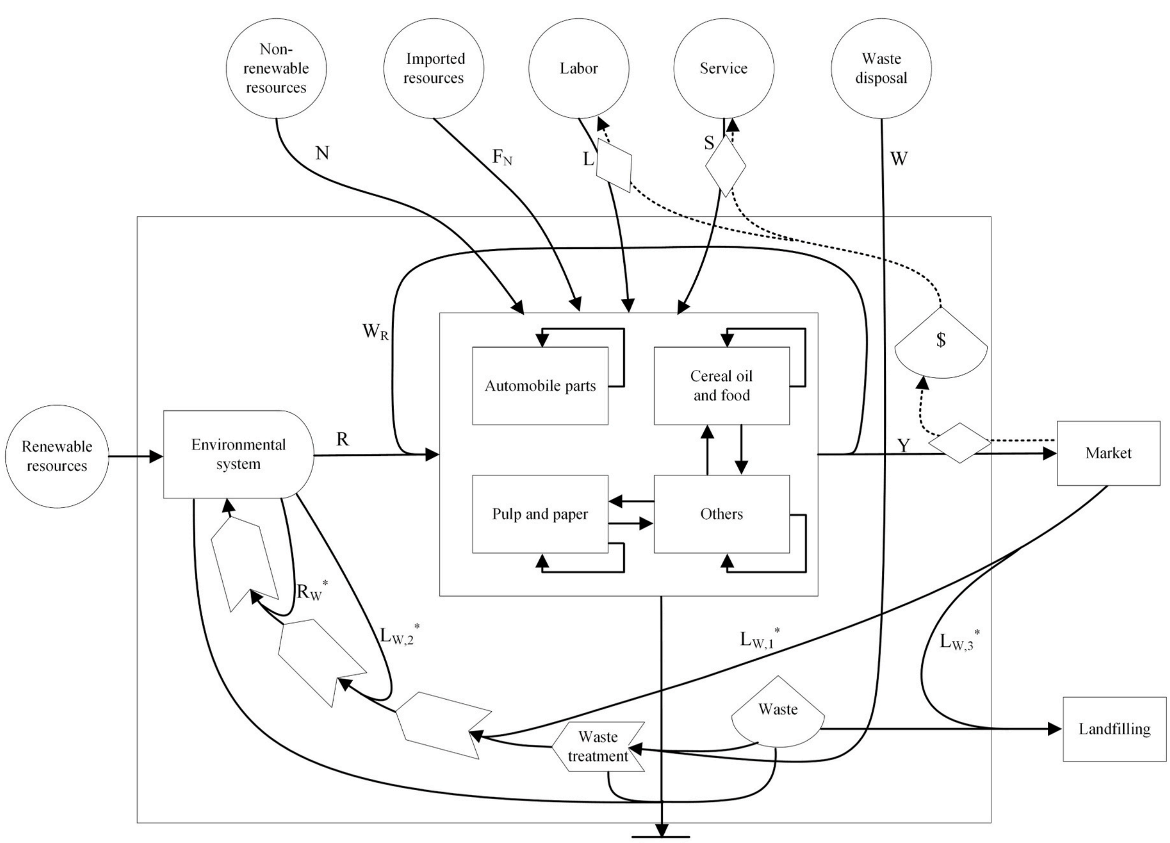

Fig. 1. Emergy system diagram of RETDA.

Table 1
Ecological services provided by environmental dilution.

Item	Acceptable concentration	References
Air pollutants		
Dust	200 μg/m^3	MEE (2012)
SO_2	60 μg/m^3	MEE (2012)
NO_X	50 μg/m^3	MEE (2012)
Seawater pollutants		
COD	4 mg/L	MEE (1997)
Total phosphate	0.3 mg/L	MEE (1997)
Arsenic	0.05 mg/L	MEE (1997)
Surface water pollutants		
COD	30 mg/L	MEE (2002)
NH_4–N	1.5 mg/L	MEE (2002)
Total phosphate	0.3 mg/L	MEE (2002)

Finally, various pollutants can be diluted simultaneously; thus, the maximum emergy of the two environmental media is selected to avoid double counting. The total emergy of the ecological service (R_W*) is the sum of the aforementioned two maximums.

N_{chem} is the chemical available energy of water, G is the Gibbs free energy per unit mass of water, and $Tr_{water,\ chem}$ is the transformity of water chemical potential.

2.2.3. *Quantification of emergy loss of emissions*

Some pollutants cause a series of ecological and economic loss, such as reducing biodiversity and affecting human health. Among them, human resources similar to ecological resources are regarded as local storage and are irreversibly lost after being harmed (Pan et al., 2016). According to the Eco-Indicator 99 assessment method, the formulas used to calculate the emergy loss of population health ($L_{W,1}$*) and ecological resources ($L_{W,2}$*) are shown in equations (5) and (6).

$$L_{W,1}{}^{*} = \sum m_i \times DALY_i \times \tau_H \tag{5}$$

$$L_{W,2}{}^{*} = \sum m_i \times PDF(\%)_i \times E_{Bio} \tag{6}$$

Here, m_i is the mass of the ith pollutant released; DALY and PDF (%) are selected from the E.I. 99 impact factors, whose values are listed in Table 2; τ_H is the unit emergy allocated to the human resource per year, calculated as τ_H = total annual emergy/population (Lou and Ulgiati, 2013); E_{Bio} is the unit emergy stored in the biological resource (sej × m^{-1} × $year^{-1}$), which is presented as the emergy of local wilderness, farming, forestry, animal husbandry, or fishery production.

In addition, the landfill for solid waste occupies land, which will cause the loss of urban capital ($L_{W,3}$*), which is attained according to the total land area occupied by the landfilled solid waste multiplied by the unit emergy value of the land area. According to Wang et al. (2006), 2.85E+04 tons of industrial solid waste landfills occupy approximately 1 ha of land in China.

Table 2
DALY and PDF values of the pollutants considered in this work (Liu et al., 2011).

Item	Damage category ecosystem quality	PDF × m^2 × year	Damage category human health	DALY/kg of emission
Air pollutants				
Dust	–	–	Respiratory disorders	3.75E−04
SO_2	Acidification	1.04E+00	Respiratory disorders	5.46E−05
NO_X	Acidification	5.71E+00	Respiratory disorders	8.87E−05
Water pollutants				
COD	Eutrophication	–	Eutrophication	–
NH_4–N	Eutrophication	–	Eutrophication	–
Arsenic	Ecotoxic emissions	1.14E+01	Carcinogenic effects	6.57E−02

2.2.4. *Emergy evaluation: the index system*

In this index system, the local and purchased inputs are not only considered but the impact of pollution discharge is also included. Resource productivity is introduced to evaluate the utilization efficiency of materials, water, and energy. The comprehensive performance of industrial symbiosis in the park can be reflected more objectively.

(1) The emergy self-sufficiency ratio (ESR, %) is defined as the emergy input of local resources divided by the total emergy input (U) of the system. It reflects the emergy structure and self-sufficiency of the industrial park (Lan, 2002). The larger this ratio, the more abundant the local resources of the system, the higher the degree of resource development, and the higher the competitiveness and self-supporting ability of the industrial park.

$$ESR = \frac{R + N}{R + N + F + E_L} \tag{7}$$

(2) Relative emergy saving ratio (RESR, %) is the ratio of the input emergy saved due to industrial symbiosis to the total input emergy without symbiosis (Geng et al., 2014). The higher this indicator value, the more complete the industrial chain of the park, the higher the utilization rate of resources, and the smaller the impact of emissions.

$$RESR = \frac{\Delta R + \Delta N + \Delta F + \Delta E_L}{R + N + F + E_L} \tag{8}$$

(3) Emission impact reduction ratio (EIRR, %) is the ratio of the reduction due to industrial symbiosis to the total impacts of emissions without symbiosis.

$$EIRR = \frac{\Delta E_L}{E_L} \tag{9}$$

(4) The emergy yield ratio (EYR) is the ratio of the total emergy input in production to the emergy input outside the system. It characterizes the effectiveness of system economic investment and measures the net benefits to the economy.

$$EYR = \frac{R + N + F + E_L}{F + E_L} \tag{10}$$

(5) Emergy-resource productivity (ERP, $/sej) accounts for gross domestic product (GDP) per unit of direct resource input, including materials, water, and energy. A high value means that more products or services can be produced with fewer resources.

$$ERP_M = \frac{GDP}{Material} \tag{11}$$

Here, ERP_M represents the material productivity of the system, and the Material represents the emergy value corresponding to the direct input material. Water productivity (ERP_W) and energy productivity (ERP_E) are obtained in the same manner.

(6) The emergy money ratio (EMR, sej/$) is the ratio of total emergy use to total GDP. It represents the emergy cost per unit of GDP, thereby evaluating the production efficiency of the system. The higher the index value, the more resources will be consumed to produce the same amount of GDP.

$$EMR = \frac{R + N + F + E_L}{GDP} \tag{12}$$

(7) Relative money saving (RMS, $) is the economic cost of saving emergy relative to EMR, which can quantify the economic benefits due to industrial symbiosis (Geng et al., 2014).

$$RMS = \frac{\Delta R + \Delta N + \Delta F + \Delta E_L}{EMR} \tag{13}$$

(8) The environmental loading ratio (ELR) represents the sum of local non-renewable emergy, purchased emergy, and emissions' impact emergy to renewable emergy (Zhang et al., 2009). It reflects the imbalance between non-renewable and renewable resources and the contribution of indirect environmental resources to the entire system. A smaller ratio indicates a greater dependence on renewable resources, and greater pressure on the system's local environmental resources. In Eq. (13), the emission loss is corrected.

$$ELR = \frac{N + N_F + E_L}{R} \tag{14}$$

(9) The emergy sustainability index (ESI) is the EYR/ELR ratio used to measure the coordination and sustainable development of industrial parks. According to the analysis standard proposed by Brown and Ulgiati (1997), the smaller the value of ESI, the more developed the economy.

$$ESI = \frac{EYR}{ELR} \tag{15}$$

3. Case study

3.1. Case background

To test the proposed method, a case study was conducted to evaluate the symbiosis benefits of Rizhao Economic-Technological Development Area (RETDA). RETDA is in the eastern coastal port city of Shandong Province. There are two streets, 89 villages (communities), and a population of 135,000 in the park, with a planned area of 115.56 km^2. Its industrial system is complete, focusing on the three leading industries of cereal oil and food, pulp and paper, and automobile parts; starting with the exchange of waste/by-products within firms; gradually establishing collaborations among different industrial companies; improving the efficiency of resource flows; and continually improving the circular supply chain network. Due to the coordinated development of the economy and the environment, RETDA has successively won national honors, such as those for the National Eco-Industry Demonstration Park, the National

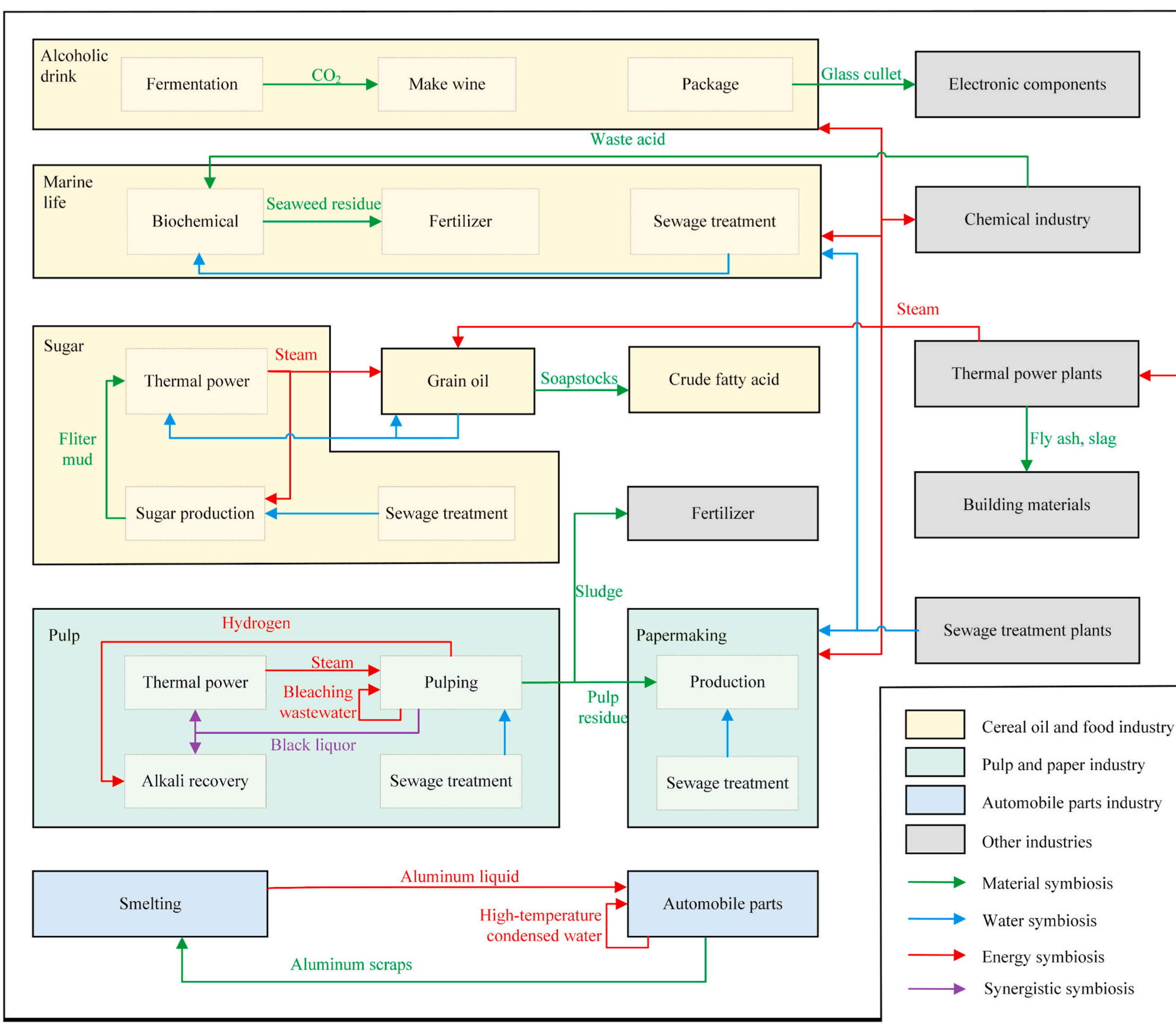

Fig. 2. Industrial symbiosis network of RETDA in 2018.

Low-Carbon Industrial Demonstration Park, and the National Recycling Demonstration Park.

3.2. Symbiosis network

The symbiosis network in RETDA is illustrated in Fig. 2. There are nine kinds of material symbiosis, three kinds of water symbiosis, five kinds of energy symbiosis, and one kind of synergistic symbiosis.

(1) Material symbiosis is the most complicated relationship, represented by green (Fig. 2). First, inside the enterprise, the brewery recycles 3.20E+03 tons of carbon dioxide produced by fermentation for the packaging process, and the sugar factory makes full use of the calcium carbonate in the filter mud to replace 7.71E+03 tons of boiler desulfurizer. Second, within the same industry, 1.19E+04 tons of saponins are reused to produce crude fatty acids; pulp residue replaces 2.83E+03 tons of pulp to make paper; and aluminum scraps are reused to smelt again, reducing the input of 9.71E+03 tons of aluminum ingots. Moreover, between different industries, it is common to use fly ash and slag produced by coal-burning enterprises to produce building materials that replace 7.93E+04 tons of sandstone, 1.38E+05 tons of clay, and 1.74E+05 tons of slag. The remaining part is the recycling of cullet, waste acid, sludge, and seaweed residue.

(2) Water symbiosis is represented by blue (Fig. 2). Some of the condensed water of grain and oil enterprises is reused to power boilers, and others are used for production and green belt sprinkling. Besides, wastewater treatment plants in enterprises and the park can provide reclaimed water for production.

(3) Energy symbiosis is shown in red (Fig. 2). 2.03E+16 J steam is used as a by-product in cogeneration to replace the coal-fired boilers of the surrounding enterprises. The excess heat contained in wastewater and high-temperature molten aluminum is used to reduce the consumption of steam and natural gas. In addition, domestic waste and by-product hydrogen replace 1.29E+04 tons of coal and 7.80E+03 tons of heavy oil.

(4) Synergistic symbiosis is the combustion of the black liquor produced in the pulping process of the papermaking enterprise, represented in purple (Fig. 2). In this process, 8.01E+05 tons of sodium salt is recovered, replacing 1.21E+06 tons of coal to release heat.

3.3. Data collection

Data in this study were collected from local statistical yearbooks, annual statistical reports on production and emissions, questionnaire surveys, environmental reports, and cleaner production reports. The overall data, such as GDP and labor, were obtained from the statistical yearbook and annual statistical reports. We issued questionnaires about production emissions to producers in the park, especially the detailed collection and summary of the symbiotic substances and quantities. In order to obtain more accurate information and understand the industrial symbiosis network of RETDA, interviews with park managers and managers of 22 key enterprises were conducted. Then clean production reports and environmental impact assessment reports were used to verify and supplement data such as raw materials and symbiosis data. Next, the collected data were classified, and their corresponding UEV was queried.

Subsequently, the input resource data without symbiosis were simulated to establish a complete emergy analysis table. Table 3 lists the RETDA's emergy accounting data for six scenarios of non-industrial symbiosis, industrial symbiosis, material symbiosis, energy symbiosis, water symbiosis, and synergistic symbiosis in 2018.

4. Results

4.1. Saving emergy compared with non-industrial symbiosis

Since becoming an eco-industrial demonstration park, RETDA has always pursued a circular economy by promoting the recycling of waste/by-products within the park that has resulted in remarkable achievements of reducing investment. As shown in Table 4, the input of 1.65E+22sej is effectively saved with industrial symbiosis. 28.23% of imported resources and 20.28% of service are avoided. Besides, the output of waste is reduced as it is reused, resulting in the consequent reduction of disposal costs and the impact of emissions by 14.73% and 30.91% respectively.

Due to the company's symbiosis awareness and feasible technologies, the synergistic symbiosis of black liquor accounts for 56.79% of the total saving. Followed by energy symbiosis (19.98%), material symbiosis (16.58%), and water symbiosis (6.65%). In the F_N, the contribution rate of synergetic symbiosis that replaces many resources is the highest, accounting for 63.14%. Although the types of material symbiosis are the most complex and diverse, the exchange volume is relatively small, and most of the raw materials to be replaced are sand, clay, straw, and other primary products that do not have much emergy accumulation. Therefore, the contribution rate was low, accounting for only 16.68%. W is related to the recycling amount of waste and the reduced disposal costs during regeneration. The reduction of solid waste in material symbiosis is higher than that of domestic waste in energy symbiosis; thus, the contribution rate of the former is higher than that of the latter.

4.2. Impact of pollution emissions

RETDA has carried out pollution remediation so that the environmental quality is continuously improved. In industrial symbiosis, the loss accounts for only 0.27% of the total emergy, that is, 1.52E+20sej. The ecological loss ($L_{W,2}$*) caused by air pollutants is the most among several items, accounting for 85.73% of the total (Table 5). NO_X in the atmosphere accounts for the absolute contribution. R_W* is 1.18E+19sej, accounting for only 7.73%. To alleviate the deterioration of the water environment, the up-to-standard wastewater of enterprises except paper mill in the area is discharged into the river after centralized treatment by sewage treatment plants, and the discharge concentration is within the allowable range of the surface water. Therefore, the water used to dilute the paper mill's wastewater directly discharged after treatment provides 95.14% of R_W*.

As shown in Fig. 3, the change of ecological service is the most significant in emergy loss compared with non-industrial symbiosis. Although water symbiosis contributes the least to the total saving emergy, it is the main force in reducing the impact of emissions accounted for 99.10%. Without symbiosis, the reused water and black liquor are simulated as wastewater discharge into the sea after biochemical treatment, which requires ecological dilution and harms the environment and human health. However, the black liquor of 2.69E+06 tons is two orders of magnitude smaller than the reduction in water symbiosis. Therefore, the emergy of R_W*, $L_{W,1}$*, and $L_{W,2}$* saved by synergistic symbiosis are all less than 1%. In $L_{W,3}$*, 89.00% of solid waste is reused in material symbiosis, playing a role in avoiding land occupation loss. The rest is caused by domestic waste weighing 5.69E+04 tons used for power generation.

4.3. Index system

The relevant indicators are listed in Table 6. In the improved system, the relative emergy saving ratio is 23.18% and the environmental impact is reduced by 30.91% through the reuse of internal waste or by-products. However, the ESR with industrial symbiosis remains less than 5%, which reflects that due to the limited natural resources in the park, the current economic development of RETDA relies on the input of

Table 3
The emergy analysis table of RETDA.

Item	Amount	Units/yr	UEV (sej/unit)	Solar emergy (sej/yr)					
				Non-industrial symbiosis	Industrial symbiosis	Material symbiosis	Water symbiosis	Energy symbiosis	Synergistic symbiosis
Local renewable resources (R)									
1. Sunlight	5.38E+16	J	1.00E+00	5.38E+16	5.38E+16	5.38E+16	5.38E+16	5.38E+16	5.38E+16
2. Wind	2.85E+13	J	1.90E+03 [a]	5.42E+16	5.42E+16	5.42E+16	5.42E+16	5.42E+16	5.42E+16
3. Rain, chemical	6.45E+13	J	2.65E+04 [a]	1.71E+18	1.71E+18	1.71E+18	1.71E+18	1.71E+18	1.71E+18
4. Rain, geopotential	2.92E+10	J	1.33E+04 [a]	3.89E+14	3.89E+14	3.89E+14	3.89E+14	3.89E+14	3.89E+14
5.Air	5.43E+07	t	3.91E+13 [b]	2.13E+21	2.13E+21	2.13E+21	2.13E+21	2.13E+21	2.13E+21
6. Surface water	4.18E+07	t	1.00E+11 [c]	4.18E+18	4.18E+18	4.18E+18	4.18E+18	4.18E+18	4.18E+18
Local non-renewable resources (N)									
7. Ground water	2.74E+05	t	1.04E+12 [c]	2.85E+17	2.85E+17	2.85E+17	2.85E+17	2.85E+17	2.85E+17
8. Fishery extraction	3.56E+13	J	7.66E+06 [d]	2.73E+20	2.73E+20	2.73E+20	2.73E+20	2.73E+20	2.73E+20
9. Phaeophyta	2.61E+13	J	5.32E+05 [e]	1.39E+19	1.39E+19	1.39E+19	1.39E+19	1.39E+19	1.39E+19
Imported resources (F_N)									
10. Steam	2.07E+16	J	6.38E+04 [f]	1.32E+21	0.00E+00	1.32E+21	1.32E+21	0.00E+00	1.32E+21
11. Coal	1.95E+17	J	6.71E+04 [g]	1.31E+22	1.07E+22	1.31E+22	1.31E+22	1.31E+22	1.07E+22
12. Fuel Oil	1.26E+15	J	1.00E+05 [d]	1.26E+20	9.30E+19	1.26E+20	1.26E+20	9.30E+19	1.26E+20
13. Natural Gas	8.54E+15	J	1.06E+05 [d]	9.07E+20	3.69E+20	9.07E+20	9.07E+20	3.69E+20	9.07E+20
14. Municipal solid wastes	2.05E+05	t	3.89E+13 [h]	7.97E+18	7.97E+18	7.97E+18	7.97E+18	7.97E+18	7.97E+18
15. Tap Water	4.28E+08	t	1.92E+12 [c]	8.21E+20	1.75E+19	8.21E+20	1.75E+19	8.21E+20	8.21E+20
16. Carbon dioxide	3.20E+03	t	1.06E+15 [i]	3.39E+18	0.00E+00	0.00E+00	3.39E+18	3.39E+18	3.39E+18
17. Malt	9.51E+03	t	2.20E+15 [j]	2.10E+19	2.10E+19	2.10E+19	2.10E+19	2.10E+19	2.10E+19
18. Corn, grain	6.00E+02	t	1.10E+16 [k]	6.60E+18	6.60E+18	6.60E+18	6.60E+18	6.60E+18	6.60E+18
19. Rice	1.04E+03	t	3.39E+15 [b]	3.54E+18	3.54E+18	3.54E+18	3.54E+18	3.54E+18	3.54E+18
20. Soybeans	3.21E+06	t	1.72E+15 [l]	5.52E+21	5.52E+21	5.52E+21	5.52E+21	5.52E+21	5.52E+21
21. Fruit	4.02E+04	t	5.18E+15 [b]	2.08E+20	2.08E+20	2.08E+20	2.08E+20	2.08E+20	2.08E+20
22. Cotton	5.05E+02	t	1.75E+16 [k]	8.84E+18	8.84E+18	8.84E+18	8.84E+18	8.84E+18	8.84E+18
23. Straw	9.98E+04	t	1.82E+15 [m]	1.82E+20	0.00E+00	0.00E+00	1.82E+20	1.82E+20	1.82E+20
24. Raw sugar	2.78E+05	t	3.20E+15 [A]	8.90E+20	8.90E+20	8.90E+20	8.90E+20	8.90E+20	8.90E+20
25. Woodchips	3.91E+06	t	4.42E+14 [n]	1.73E+21	1.73E+21	1.73E+21	1.73E+21	1.73E+21	1.73E+21
26. Pulp	1.75E+04	t	2.99E+15 [n]	5.22E+19	4.37E+19	4.37E+19	5.22E+19	5.22E+19	5.22E+19
27. Paper	4.52E+04	t	4.57E+15 [n]	2.07E+20	1.83E+20	1.83E+20	2.07E+20	2.07E+20	2.07E+20
28. Aluminum	1.29E+05	t	3.36E+16 [o]	4.32E+21	3.99E+21	3.99E+21	4.32E+21	4.32E+21	4.32E+21
29. Aluminium alloy	3.32E+03	t	4.69E+16 [o]	1.56E+20	1.56E+20	1.56E+20	1.56E+20	1.56E+20	1.56E+20
30. Iron	1.57E+01	t	5.40E+15 [p]	8.47E+16	8.47E+16	8.47E+16	8.47E+16	8.47E+16	8.47E+16
31. Steel	8.90E+04	t	5.80E+15 [p]	5.16E+20	5.16E+20	5.16E+20	5.16E+20	5.16E+20	5.16E+20
32. Copper	7.35E+02	t	2.08E+16 [p]	1.53E+19	1.53E+19	1.53E+19	1.53E+19	1.53E+19	1.53E+19
33. Zinc	4.64E+02	t	2.29E+15 [b]	1.06E+18	1.06E+18	1.06E+18	1.06E+18	1.06E+18	1.06E+18
34. Zinc oxide	6.50E+00	t	5.15E+16 [b]	3.35E+17	3.35E+17	3.35E+17	3.35E+17	3.35E+17	3.35E+17
35. Silicon	4.48E+03	t	1.39E+16 [q]	6.23E+19	6.23E+19	6.23E+19	6.23E+19	6.23E+19	6.23E+19
36. Clinker	6.38E+05	t	9.70E+15 [r]	6.19E+21	6.19E+21	6.19E+21	6.19E+21	6.19E+21	6.19E+21
37. Limestone	1.76E+05	t	7.22E+15 [s]	1.27E+21	1.21E+21	1.21E+21	1.27E+21	1.27E+21	1.27E+21
38. Sandstone	7.93E+04	t	6.46E+15 [s]	5.12E+20	0.00E+00	0.00E+00	5.12E+20	5.12E+20	5.12E+20
39. Clay	1.38E+05	t	2.55E+15 [b]	3.53E+20	0.00E+00	0.00E+00	3.53E+20	3.53E+20	3.53E+20
40. Slag	1.74E+05	t	2.46E+15 [b]	4.28E+20	0.00E+00	0.00E+00	4.28E+20	4.28E+20	4.28E+20
41. Float Glass	1.09E+05	t	1.00E+16 [f]	1.09E+21	1.09E+21	1.09E+21	1.09E+21	1.09E+21	1.09E+21
42. Glass scrap	3.84E+04	t	2.42E+15 [f]	9.28E+19	2.01E+19	2.01E+19	9.28E+19	9.28E+19	9.28E+19
43. Caustic soda	9.06E+05	t	7.66E+15 [n]	6.94E+21	8.01E+20	6.94E+21	6.94E+21	6.94E+21	8.01E+20
44. Hydrochloric acid	6.80E+04	t	4.63E+15 [t]	3.14E+20	2.97E+19	2.97E+19	3.14E+20	3.14E+20	3.14E+20
45. Sulfuric acid	2.36E+04	t	6.80E+15 [p]	1.60E+20	1.60E+20	1.60E+20	1.60E+20	1.60E+20	1.60E+20
46. KCl	1.00E+00	t	1.18E+15 [n]	1.18E+15	1.18E+15	1.18E+15	1.18E+15	1.18E+15	1.18E+15
47. Chlorine	1.23E+04	t	3.43E+14 [n]	4.23E+18	4.23E+18	4.23E+18	4.23E+18	4.23E+18	4.23E+18
48. Sodium carbonate	4.04E+04	t	2.62E+15 [n]	1.06E+20	1.06E+20	1.06E+20	1.06E+20	1.06E+20	1.06E+20
49. Sodium sulfate	6.07E+04	t	3.19E+12 [n]	1.94E+17	1.94E+17	1.94E+17	1.94E+17	1.94E+17	1.94E+17
50. Starches	8.00E+02	t	6.78E+10 [n]	5.42E+13	5.42E+13	5.42E+13	5.42E+13	5.42E+13	5.42E+13
51. Aluminum sulfate	3.00E+02	t	2.01E+15 [n]	6.03E+17	6.03E+17	6.03E+17	6.03E+17	6.03E+17	6.03E+17
52. Lubrificant oil	5.90E+03	m^3	4.67E+15 [n]	2.75E+19	2.75E+19	2.75E+19	2.75E+19	2.75E+19	2.75E+19
53. Rosin	2.00E+02	t	4.83E+14 [n]	9.66E+16	9.66E+16	9.66E+16	9.66E+16	9.66E+16	9.66E+16
54. HDPE	9.31E+03	t	6.70E+15 [f]	6.24E+19	6.24E+19	6.24E+19	6.24E+19	6.24E+19	6.24E+19
55. Other plastic	1.02E+03	t	7.46E+14 [u]	7.58E+17	7.58E+17	7.58E+17	7.58E+17	7.58E+17	7.58E+17
56. Hexane	1.67E+03	t	7.73E+15 [u]	1.29E+19	1.29E+19	1.29E+19	1.29E+19	1.29E+19	1.29E+19
57. Bentonite	3.34E+03	t	1.27E+15 [l]	4.25E+18	4.25E+18	4.25E+18	4.25E+18	4.25E+18	4.25E+18
58. Soapstock	1.10E+05	t	3.89E+13 [h]	4.28E+18	3.82E+18	3.82E+18	4.28E+18	4.28E+18	4.28E+18
Labor (L)	1.68E+09	$	4.46E+12 [b]	7.49E+21	7.49E+21	7.49E+21	7.49E+21	7.49E+21	7.49E+21
Service (S)	2.36E+10	$	4.46E+12 [b]	1.43E+22	1.14E+22	1.41E+22	1.41E+22	1.23E+22	1.38E+22
Waste disposal (W)	1.00E+08	$	4.46E+12 [b]	4.48E+20	3.82E+20	4.47E+20	3.83E+20	4.48E+20	4.48E+20

ãs were selected from the following references. The adopted emergy baseline was 12.00E+24sej/a.
a (Odum, 2000); b (Geng et al., 2014); c (Liu et al., 2019); d (NEAD, 2014); e (Berrios et al., 2017); f (Buranakarn, 1998); g (Fan et al., 2017); h (Liu et al., 2017); I (Maiolo et al., 2021); j (Gao et al., 2012); k (Williams, 2000); l (Cavalett and Ortega, 2009); m (Wang et al., 2014); n (Corcelli et al., 2018); o (Liu and Yang, 2018); p (Jing et al., 2020); q (Corcelli et al., 2017); r (Mikulčić et al., 2016); s (Odum, H.T., 2000); t (Jiménez Borges et al., 2020); u (Odum, 1996).
A was calculated in this study. Raw sugar is obtained by squeezing the sugarcane. For 1t raw sugar, the required masses of sugarcane, freshwater, and coal are 8t, 16t, and 0.4t, respectively.

Table 4
Saving emergy of each flow in five symbiosis scenarios.

Emergy flows (sej)		Non-industrial symbiosis[a]	Saving emergy[b]				
			Industrial symbiosis[c]	Material symbiosis[d]	Water symbiosis[e]	Energy symbiosis[f]	Synergistic symbiosis[g]
Local renewable resources	R	2.13E+21	–	–	–	–	–
Local non-renewable resources	N	2.87E+20	–	–	–	–	–
Imported resources	F_N	4.78E+22	1.35E+22	2.25E+21	8.04E+20	1.92E+21	8.52E+21
Labor	L	7.49E+21	–	–	–	–	–
Service	S	1.43E+22	2.90E+21	2.46E+20	1.90E+20	1.43E+21	1.09E+21
Waste disposal	W	4.48E+20	6.60E+19	3.11E+20	6.45E+19	3.83E+19	2.84E+17
The impacts of emissions	E_L	2.20E+20	6.80E+19	1.28E+16	6.66E+19	1.59E+15	5.91E+17
The total emergy input	U	7.26E+22	1.65E+22	2.81E+21	1.12E+21	3.38E+21	9.61E+21

[a] lists the emergy flows under the assumption that there is no symbiosis in RETDA.
[b] represents the emergy saved in five scenarios compared with non-industrial symbiosis.
[c] contains all symbiotic relationships in RETDA.
[d ~ g] assume that there is only the corresponding symbiosis, without other types in RETDA.

Table 5
Emergy loss of pollutants with industrial symbiosis.

Item	R_W* (sej)[a]	$L_{W,1}$* (sej)[b]	$L_{W,2}$* (sej)[c]	$L_{W,3}$* (sej)[d]	E_L (sej)[e]
Air pollutant	5.73E+17	9.96E+18	1.31E+20	–	1.41E+20
Dust	1.59E+16	3.06E+18	0.00E+00	–	
SO_2	4.27E+16	3.59E+17	2.09E+18	–	
NO_X	5.73E+17	6.53E+18	1.29E+20	–	
Water pollutant	1.12E+19	5.89E+14	3.13E+13	–	1.12E+19
COD	1.12E+19	–	–	–	
Arsenic	–	5.89E+14	3.13E+13	–	
Solid waste	–	–	–	7.74E+14	7.74E+14
Total	1.18E+19	9.96E+18	1.31E+20	7.74E+14	1.52E+20

[ãe] indicate different emergy loss (R_W*: the ecological service; $L_{W,1}$*: the emergy loss of population health; $L_{W,2}$*: the emergy loss of ecological resources; $L_{W,3}$*: the emergy loss of urban capital; E_L: the impacts of emissions).

external resources. EYR shows an upward trend because of reduced purchase investment and increased economic efficiency.

Due to too much pressure brought by many high water and energy consumption enterprises such as thermal power plants, the park had to implement a series of measures to optimize resource allocation. On the one hand, the government has perfected infrastructure construction through central heating and urban reclaimed water projects; on the other hand, the companies have actively carried out clean production to maximize the utilization efficiency of materials and energy. As a result, ERP_M, ERP_W, and ERP_E are increased by 0.33, 36.50, and 0.38, respectively. Symbiosis types and resource productivity use the same classification criteria that focus on the types of direct input resources, including materials, water, and energy. In a single symbiosis, changes in productivity have a certain relevance with types (Fig. 4). ERP_W is increased by 36.57 times in water symbiosis. It replaces 97.34% of the external water input and improves water utilization. Furthermore, the recovery of black liquor realizes the material-energy symbiosis so that ERP_M and ERP_E are simultaneously increased.

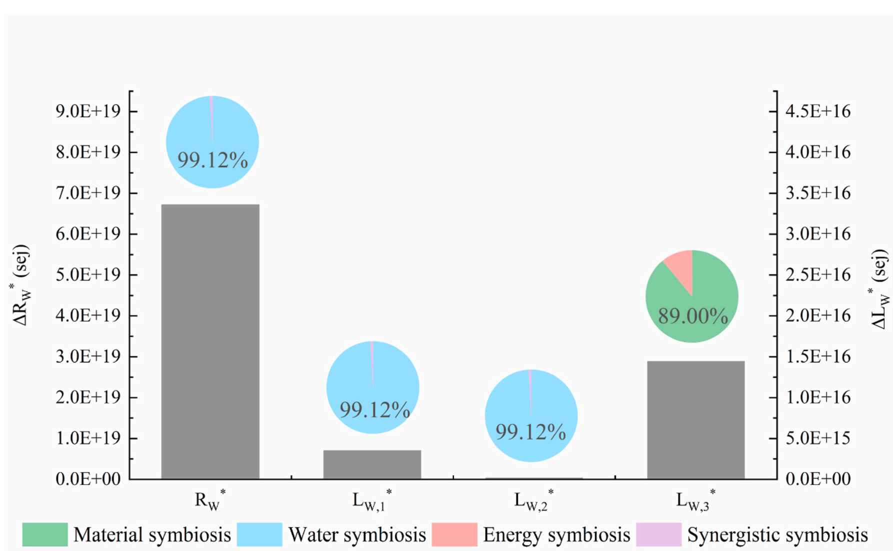

Fig. 3. Changes in emergy loss compared with non-industrial symbiosis.

Table 6
Emergy indicators for non-industrial symbiosis and industrial symbiosis.

Indicators and units		Improved indicators		Classic indicators	
		Non-industrial symbiosis	Industrial symbiosis	Non-industrial symbiosis	Industrial symbiosis
Emergy self-sufficiency ratio	ESR (%)	3.31	4.31	3.32	4.32
Relative emergy saving ratio	RESR (%)	–	23.18	–	23.16
Emission impact reduction ratio	EIRR (%)	–	30.91	–	–
Emergy yield ratio	EYR	1.0343	1.0451	1.0344	1.0452
Emergy-material productivity	ERP_M ($/sej)	2.63E-13	3.49E-13	–	–
Emergy-water productivity	ERP_W ($/sej)	1.08E-11	4.05E-10	–	–
Emergy-energy productivity	ERP_E ($/sej)	5.76E-13	7.97E-13	–	–
Emergy money ratio	EMR (sej/$)	8.20E+12	6.30E+12	8.17E+12	6.28E+12
Relative money saving	RMS ($)	–	2.69E+09	–	2.68E+09
Environmental loading ratio	ELR	33.25	25.31	33.15	25.24
Emergy sustainability index	ESI	0.0311	0.0413	0.0312	0.0414

In doing so, the economic input cost of 2.69E+09$ (equivalent to 30.18% of GDP) is saved, and the environmental load of 23.88% is reduced in RETDA. Based on the respective trends of EYR and ELR, the ESI is increased by 32.74%. In general, industrial symbiosis promotes the sustainable development of parks.

5. Discussion and implications

With the above analysis, it is verified that the level of sustainable development is promoted through the symbiosis implemented in RETDA. As discussed in the introduction, the improved method expands the breadth and depth of quantifying the benefits of industrial symbiosis with traditional emergy analysis.

From the comprehensiveness of the assessment, the symbiosis performance can be quantified from multiple perspectives, such as resource utilization, pollution emissions, economic investment, environmental load, and sustainable development. On the one hand, the added indicators, including ERP_M, ERP_W, and ERP_E, reflect the productivity of materials, water, and energy, respectively, and their consumption in the park. The optimization of resource utilization efficiency can be tested by comparing the changes before and after the implementation of the measures. In the traditional emergy indicators, the influential role that water symbiosis can increase ERP_W by 36.57 times is ignored because its saving emergy is smaller than that for the other types. On the other hand, the impact of emissions is considered in emergy flows, thereby improving the index system to more accurately reflect the status quo of the park. Comparing the two scenarios with and without symbiosis in RETDA, the quantified benefit of emission reduction is that the environmental impact is reduced by 30.91%. Furthermore, RESR and RMS have slightly improved to more comprehensively demonstrate the benefits of symbiosis in emission reduction. The declining EYR, ESI, and the increased ELR also reflect the environmental pressure caused by emissions. However, with the increasing emphasis on environmental protection, stricter environmental standards and ultra-low emission standards have been implemented in RETDA. Therefore, the changes between the traditional and improved indicators are not obvious.

From the perspective of detailed evaluation, industrial symbiosis is divided into four types according to the exchange of materials, water, and energy between symbiosis units. By analyzing the contribution characteristics of each symbiosis type, the symbiosis benefits are more concrete. It is found that the environmental performance of water symbiosis in RETDA is outstanding, increasing the water use efficiency by 36.57 times and reducing the emissions' impact by 30.32%. Synergistic symbiosis saves 8.52E+21 sej of imported resources, which can make full use of the effective components compared to only recycling alkali (6.14E+21 sej) or only replacing coal (2.38E+21 sej). Material symbiosis based on a relatively complete ecological industrial network and energy symbiosis mainly based on cogeneration can improve the utilization efficiency of materials and energy respectively.

The improved method based on emergy analysis can objectively quantify the production, service, and loss in industrial parks, and provide park managers with a comprehensive evaluation tool for industrial symbiosis performance. The performance is intuitively displayed by indicators, promoting the concept of industrial symbiosis. By analyzing the contribution of symbiosis types, managers can understand current resource usage and propose resource policies in a targeted manner to provide decision-making references for the planning and deployment. In

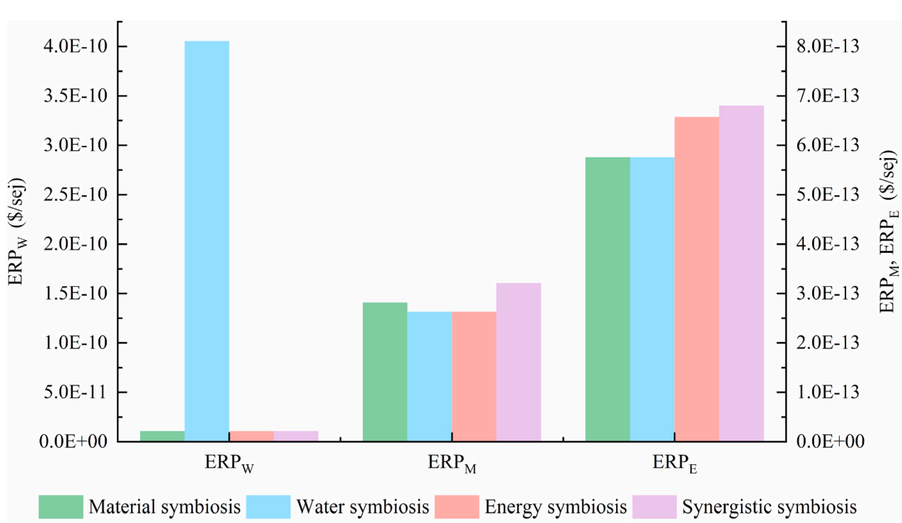

Fig. 4. Resource productivity in four scenarios.

addition, this method can also be applied in the evaluation of other energy-saving measures in industrial parks.

The proposed symbiosis taxonomy can be used to tease out and build a symbiosis network for sustainable industrial development. Through application in RETDA, many management insights can be drawn from the four symbiosis types.

First, industrial parks have high water consumption and produce serious water pollution (Hu et al., 2019). However, reclaimed water in China's industrial parks accounts for only 3.1% of the used water (Guo et al., 2020). Therefore, in parks, especially high water-consuming parks, promoting water reuse/recycle in accordance with the needs of production for water quality has a positive effect on optimizing water resource management. In addition, the park management committee can actively guide the communication between water-demanding companies and sewage treatment plants on the establishment of pipeline network facilities to promote the reuse of reclaimed water. Second, synergistic symbiosis can be created as much as possible to achieve maximum effectiveness. Analyze the characteristics of exchanged resources from multiple angles, prioritizing the possibility of synergistic symbiosis to ensure that the available components are not wasted. Third, promote industrial structure upgrading to enrich material symbiosis. The park should give full play to its industrial characteristics, improve technological level (Lessard et al., 2021; Wang et al., 2021), introduce new industrial projects (Cao et al., 2020; Sellitto and Murakami, 2018) to compensate for the shortcomings, and form a closed-loop system of "producer-consumer-decomposer" as much as possible. Finally, cogeneration and garbage power are effective measures to develop energy symbiosis relationships. Cogeneration can prevent air pollution and improve environmental quality (Li et al., 2017). Besides, because more than 80% of the parks have energy infrastructure in China (Hu et al., 2020), replacing other fuels with household waste to generate electricity can be considered in planning to alleviate the pressure on land resources in densely populated areas.

6. Conclusions

A method for assessing the comprehensive performance of an industrial park with the implementation of industrial symbiosis has been presented in this paper. Emergy analysis of the industrial symbiosis performance in the park is improved by adding resource productivity and considering the impact of emissions, and contribution recognition pathways are enriched through the presented indicators. In addition, industrial symbiosis is divided into material symbiosis, water symbiosis, energy symbiosis, and synergistic symbiosis according to the exchanged materials, water, and energy between symbiosis units. A case study at an eco-industrial park in China was carried out to test the method. The results show that industrial symbiosis has a positive effect on improving the park's sustainability. For the environment, while saving resources and improving utilization, symbiosis reduces ecological loss caused by emissions and eases the pressure of industrial production in the local environment. Economically, investment and the costs of pollution control are reduced and production efficiency is improved. Referring to the contribution differences among symbiosis types, the corresponding suggestions are presented for building a symbiosis network. Implementing the proposed method to assess the performance of industrial symbiosis will make significant progress in promoting industrial symbiosis and sustainable industrial development. Compared with the traditional emergy analysis, this method evaluates the environmental and economic benefits of industrial symbiosis in a more comprehensive and detailed manner. It can also provide a useful tool for park managers to verify the effects of other policies after implementation.

CRediT authorship contribution statement

Xinyi Chen: Conceptualization, Methodology, Investigation, Writing – original draft. **Miaoxin Dong:** Formal analysis. **Long Zhang:** Data curation. **Xiaoyu Luan:** Formal analysis. **Xiaowei Cui:** Investigation. **Zhaojie Cui:** Project administration, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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