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Study on the Choice of Wastewater Treatment Process Based on the Emergy Theory

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Abstract: With the increase in industrialization and urbanization, water pollution has become increasingly serious, and wastewater treatment has become a common step in preventing this. For a greater understanding of the sustainability of different wastewater treatment systems, two processes, Anaerobic Baffled Reactor + Anaerobic-Anoxic-Oxic and Anaerobic Baffled Reactor + Cyclic Activated Sludge System, were selected, and their sustainability was evaluated based on three indicators, namely emergy yield ratio, environmental load rate, and emergy sustainability development index, according to emergy theory. The results show that the emergy yield ratio and environmental load rate of the ABR + CASS process were lower than those of the ABR + A2/O process, and the emergy sustainability development index of the ABR + CASS process was higher than that of the ABR + A2/O process, showing better sustainability. The research methods and findings of this study play an important role for decision makers in selecting sustainable wastewater treatment processes.

Keywords: emergy analysis; wastewater treatment; sustainability



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1. Introduction

The World Water Development Report, released in March 2018, states that global water demand is increasing at an annual rate of 1% due to factors such as population growth, changes in economic development patterns, and diversification of consumption patterns [1]. China has very few available freshwater resources, and the per capita water resources are only a quarter of the world average. The development of industry and urbanization has increased the discharge of industrial wastewater and domestic sewage [2,3], leading to serious water shortages and water environmental pollution [4], and threatens the development of the economy and human and ecosystem health [5]. Urban wastewater treatment has become an important way to achieve the sustainable development of water resources.

Wastewater treatment plants play a vital role in decreasing pollution in the water environment by decreasing the concentration of pollutants in sewage and other sources via specific treatment processes. Wastewater treatment plants consume a large amount of energy and materials to treat wastewater during operation, regardless of whether they are newly built or have been in operation for many years [6]. The underground pipelines in older urban areas are simply shaped, and the layout of the existing wastewater network is unreasonable, causing the present wastewater treatment facilities in China to have issues, such as uneconomic scale configurations, low load rates, high treatment costs, low drainage

standards, and excessive energy consumption [7]. To ensure a safe and stable operation, high-quality effluent, and sludge water content of appropriate standards, decreasing the energy consumption and further pollution of the environment by wastewater treatment is a top priority for urban wastewater treatment plants. The wastewater treatment process used is vital to the success of wastewater treatment plants. Choosing the ideal treatment process is directly related to the plant effluent quality, stability of the operation, high or low operating costs, management difficulty, and the environmental impact. Therefore, it is imperative to study the influence of the wastewater treatment process on the environment and create systems with high efficiency and sustainability and low consumption [8].

Recently, the relationship between the wastewater treatment industry and the environment from a sustainability perspective has received extensive attention from scholars. Field observations, questionnaires, interviews, and laboratory tests have been used to assess the sustainability of the collective public semi-centralized wastewater treatment system in Kigali [9]. A multi-criteria, participatory approach was used to assess the sustainability of many different wastewater treatment technologies for decentralized settlements in the urban fringe of Surat [10]. Gronlund explored the sustainability of wastewater and sludge management from a systems ecology perspective [11]. A framework for evaluating the renewability of production systems based on a unified ecological evaluation approach embodying cosmic exergy analysis was presented and validated using an artificial wetland wastewater treatment system in Beijing [12].

Based on logarithmic fuzzy preference planning, fuzzy hierarchical analysis, and topologic theory, a sustainability evaluation framework for urban sludge treatment technology was developed [13]. The weighted Russell directional distance model was applied to the eco-efficiency evaluation of real wastewater treatment plants [14]. The U.S. Environmental Protection Agency's Energy Use Assessment Tool and the Korean Environment Corporation's Wastewater Treatment Plant Energy Diagnostic Tool were used to analyze the energy consumption status and excessive consumption processes of wastewater treatment plants [15]. Many scholars have used Life Cycle Assessment (LCA) methods to analyze the sustainability of wastewater treatment [16–19].

These previous studies used different methods to evaluate the sustainability of the wastewater treatment industry, which has played a positive role in reducing environmental pollution from the wastewater treatment process. However, these studies lack a unified measurement standard for various pollutants in wastewater when studying the measurement of losses brought by wastewater treatment to the ecological environment, and it is difficult to uniformly evaluate different treatment methods. It is difficult to measure the evaluation of different treatment methods. The emergy analysis method converts the products or services provided by various economic and environmental systems into the same scale [20], provides quantitative support for ecosystem evaluation, and has been widely used to evaluate agroecosystems [21,22], industrial systems [23–25], and eco-economic systems [26,27] in different countries and regions. For wastewater treatment, many scholars have conducted sustainability studies based on emergy theory. The relationship between wastewater ecological damage and economic development was discovered by analyzing wastewater discharge data using the emergy analysis method [28]. Taking a new typical wastewater treatment plant as an example, a series of integrated emergy indicators was used to evaluate the environmental sustainability of the wastewater treatment system regarding its unique technical production process [29]. Eco-efficiency indices based on emergy and LCA were used to assess the sustainable use of two wastewater treatment plants [30]. A wastewater treatment system of straw pulp papermaking and a wastewater treatment system of printing, dyeing, and papermaking were selected to evaluate the sustainability level of wastewater treatment systems in China, based on a hybrid neural network and emergy analysis framework [31]. The emergy approach has also compared two management schemes for biosolids generated from wastewater treatment plants [32]. Improved evaluation indicators based on emergy analysis were created to compare the

sustainability of different wastewater treatment processes [33] and evaluate the wastewater treatment system of a sugar mill in Kenya [34].

The present study compared and analyzed the emergy yield ratio (EYR), environmental load rate (ELR), and emergy sustainability development index (ESI), from a sustainable development perspective, of two waste water management systems, based on the emergy theory, to facilitate the selection of a more suitable wastewater treatment process. Such a study is vital to improve the urban ecological environment, achieve sustainable development of the economy, and improve the quality of life for residents.

2. Materials and Methods

2.1. Emergy Analysis Method

Emergy analysis is an energy-centered system analysis method that measures the value of any resource, product, or service relating to the amount of solar energy that is required directly and indirectly during the formation process, in solar joules (sej). The proposed emergy theory enabled macroscopic evaluation of the production of the natural environment and human economic activities using the same metric, thus enabling quantitative analysis of the structural functions and benefits of the system of interest.

The emergy inputs to the wastewater treatment ecosystem included renewable resource emergy, non-renewable resource emergy, and human economic and social feedback resource emergy, and the emergy outputs were reclaimed water and dewatered sludge treatment. Accordingly, the emergy flow diagram of the wastewater treatment ecosystem is shown in Figure 1.

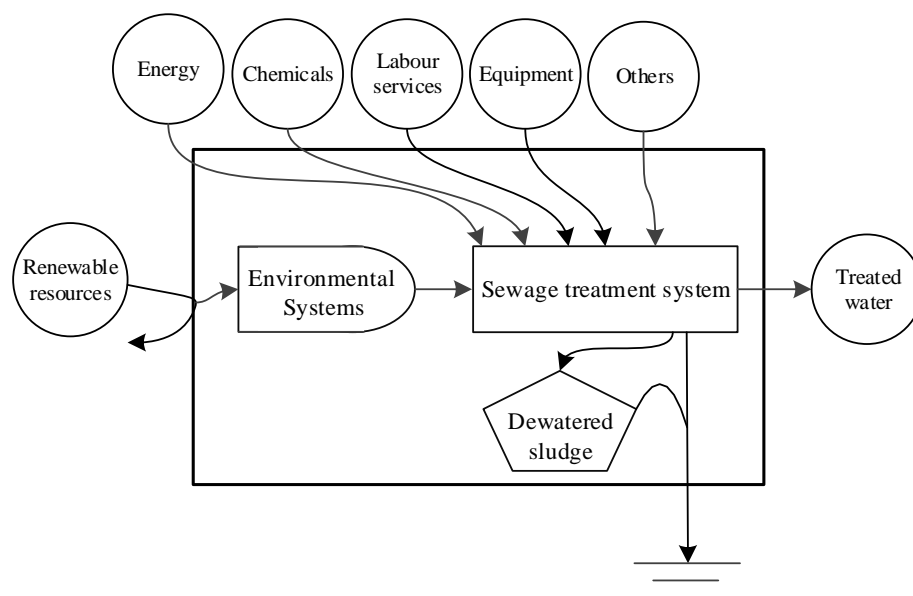


Figure 1. Diagram of the wastewater treatment ecosystem energy analysis system.

2.2. Selection of Indicators

- (1) EYR (Emergy Yield Ratio): Ratio of the amount of emergy produced by a wastewater treatment system to the amount of emergy purchased from society. The core value of a wastewater treatment system is to prevent ecological and human health damage caused by the direct discharge of wastewater; therefore, its yield includes reclaimed water and dewatered sludge. It is calculated as follows:

$$\text{EYR} = \text{EM}_Y / \text{EM}_F \quad (1)$$

where EM_Y is the yield emergy of the wastewater treatment system and EM_F is the economic feedback input resource emergy, i.e., the purchase emergy. A larger EYR value means a higher emergy yield under a certain emergy input. The higher the

production efficiency, the higher the corresponding economic benefits, reflecting that the system has higher market competitiveness.

- (2) ELR (Environmental Load Rate): Sum of non-renewable resource emergy and purchased emergy divided by the renewable resource emergy, expressed as follows:

$$\text{ELR} = (\text{EMN} + \text{EMF}) / \text{EMR} \quad (2)$$

where EM_N is the non-renewable resource emergy and EM_R is the renewable resource emergy. The main purpose of a wastewater treatment system is to eliminate or relieve environmental stress. ELR represents the magnitude of the stress caused by the treatment process on the environment [35], and a higher value means that the operational process of the wastewater treatment system is causing more stress to the environment. To avoid too great an impact of the wastewater treatment process on the environment and irreversible degradation or loss of function, the system cannot be subjected to a high ELR for a long period.

- (3) ESI (Emergy Sustainability development Index): Sustainable development requires a high level of beneficial output for a given resource input, while maintaining a low level of environmental stress; therefore, the ESI is the ratio of the EYR to the ELR, expressed as follows:

$$\text{ESI} = \text{EYR} / \text{ELR} \quad (3)$$

ESI is used to measure the sustainability of an activity [36]. A higher ESI means that the system is more effective and shows better sustainability under certain conditions.

3. Case Study

3.1. Background

In China, the shortcomings of the traditional activated sludge method include high infrastructure, operational costs, and energy consumption; complicated management; easy occurrence of sludge expansion and floating; inability to remove nitrogen, phosphorus, and other inorganic nutrients quickly, resulting in serious long-term environmental pollution; process equipment failing to meet the requirements of high efficiency and low consumption; and huge wastewater collection far exceeding its own investment value, causing great waste. Referring to similar wastewater treatment processes and operation practices in China, two common wastewater treatment processes, the ABR + A2/O (Anaerobic Baffled Reactor + Anaerobic-Anoxic-Oxic) process and ABR + CASS (Anaerobic Baffled Reactor + Cyclic Activated Sludge System) process, were selected as the comparison scheme, and the EYR, ELR, and ESI of the two processes were compared. The required data related to wastewater treatment process were obtained with the help of relevant staff.

3.2. Principles and Advantages of the Two Wastewater Treatment Processes

3.2.1. ABR + A2/O Process

Wastewater is collected by the pipe network and enters the grille, removing floating matter and large granular and fibrous impurities in the wastewater and protecting the normal operation of pumps and other treatment facilities. The water from the grille is lifted by the submersible wastewater pump to the grease and sand trap, which removes suspended matter and inorganic particles with large particle sizes and some grease, reducing the impact on the subsequent biological treatment facilities. After that, it enters the anaerobic baffled reactor (ABR tank), where the organic matter is degraded to CO_2 and CH_4 through anaerobic fermentation, hydrolysis, and methanation, and most of the remaining organic matter is transformed into soluble low-molecular-weight organic matter, which can be easily absorbed and transformed by organisms. The effluent from the ABR tank flows into the anaerobic/anoxic/aerobic system (A2/O reaction tank), where the residual organic matter is degraded and nitrogen and phosphorus are removed. Simultaneously, lime is added to the discharge channel of the aerobic tank according to the phosphorus concentration of the effluent to ensure the phosphorus concentration of the effluent meets

the standard. After completing the solid–liquid separation in the secondary sedimentation tank, the supernatant enters the contact disinfection tank while retaining part of the sludge, and the disinfected effluent is then discharged to the receiving waterbody. Considering the high-quality water requirements of the present study, a sand filter was added after the secondary sedimentation tank to remove pollutants if the effluent did not meet the standard. The floating sludge from the grease trap, ABR tank, and A2/O reactor was sent to the sludge treatment system via the sludge transfer pump. The process flow is shown in Figure 2.

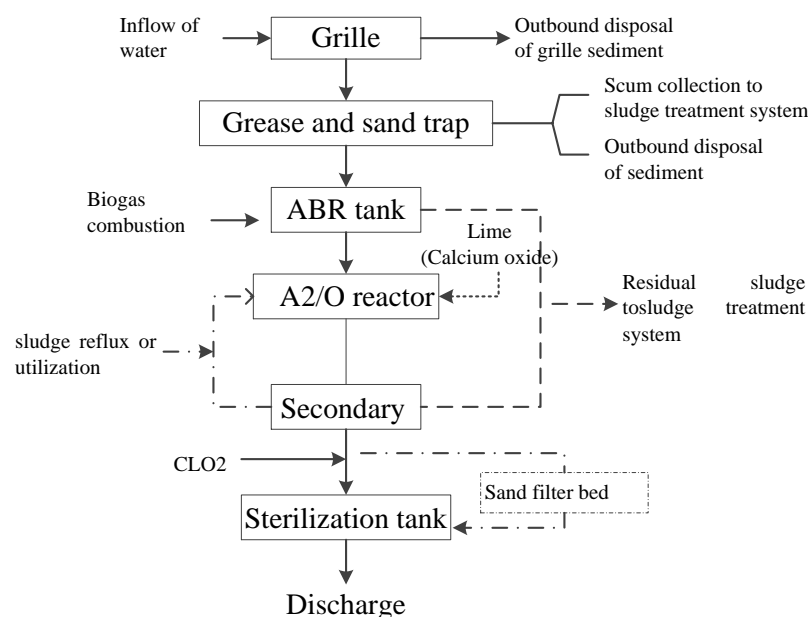


Figure 2. ABR + A2/O process flow diagram.

Main advantages of the ABR + A2/O process:

- The anaerobic component of the ABR tank involves a simple, low-investment process that does not require expensive influent systems and complexly designed three-phase separators, nor mechanical mixing devices and additional clarification and sedimentation tanks of conventional anaerobic digesters.
- Good biodistribution and biosolid retention capacity with good hydraulic mixing conditions.
- No sludge bulking.
- A2/O tank with micro-perforated aeration pipe and high oxygen utilization.
- The process is mature and reliable, and the treatment effect is stable.

3.2.2. ABR + CASS Process

The anaerobic component of this process adopts the same ABR process as the above process, whereas the aerobic component adopts the CASS process. CASS is an updated variant of SBR (Sequencing Batch Reactor). The effluent from the ABR tank flows into the pre-reaction tank in front of the CASS tank, where most of the soluble biological oxygen demand in the effluent is adsorbed by the activated sludge microorganisms and enters the reaction zone at a low flow rate via a hole in the lower partition wall of the main and pre-reaction zones. The operation process of the main reaction zone is similar to that of SBR. It is operated in a cycle of “aeration, idling, sedimentation, and drainage”, so that the wastewater is decarbonized, de-nitrogenized, and de-phosphorized in a repeated process of “aerobic–anoxic” to further remove any pollutants in the water. The effluent is disinfected and then discharged into the receiving water body. The grille sediment, primary sedimentation tank sediment, and residual sludge of the ABR tank and CASS tank are moved to the sludge treatment system by the sludge transfer pump. The process flow is shown in Figure 3.

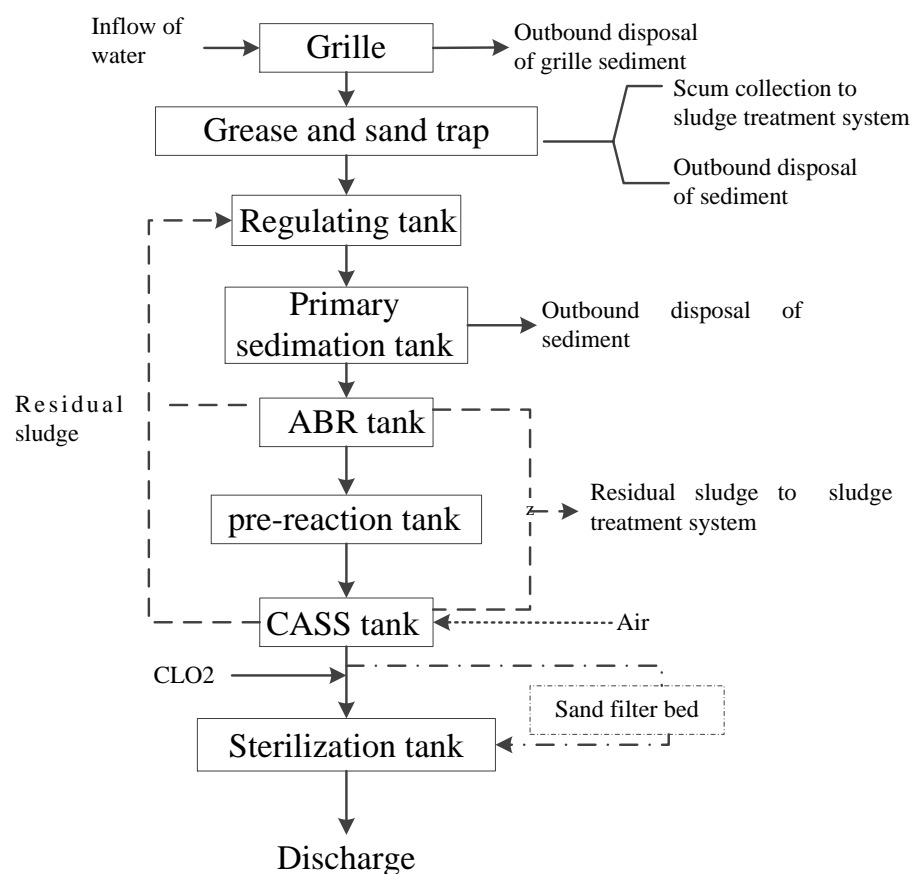


Figure 3. ABR + CASS process flow diagram.

The ABR + CASS process has the following main advantages:

- Aerobic tank part does not require a secondary sedimentation tank or regulating and primary sedimentation tanks, has no secondary sedimentation tank or sludge reflux equipment, has a compact layout of wastewater treatment facilities, and has a relatively small overall area and low investment.
- Designed with flow variation in mind, it is flexible in operation and shock resistant, achieving different treatment goals.
- The biochemical reaction has a high driving force, good sedimentation effect, a small amount of residual sludge, and a stable nature.

3.3. Results

The raw data of the two wastewater treatment processes were collected from field research, converted into the corresponding energy (unit: J or g), and then each energy was multiplied by the emergy conversion rate to obtain the solar energy of each energy. The relevant calculation results are shown in Tables 1 and 2.

Table 1. ABR + A2/O process energy analysis table.

Item	Basic Data	Emergy Conversion Rate	Solar Energy	Reference
Solar energy (J)	3.99×10^{13}	1	3.99×10^{13}	[20]
Wind energy (J)	1.25×10^{10}	6.63×10^2	8.29×10^{12}	[20]
Rainwater chemical energy (J)	5.13×10^{10}	1.54×10^4	7.90×10^{14}	[20]
Geothermal energy (J)	2.15×10^{10}	2.90×10^4	6.24×10^{14}	[20]
Hydroelectricity (J)	2.79×10^{12}	1.29×10^5	3.60×10^{17}	[37]
Labor service (CNY)	9.46×10^5	8.61×10^{11}	8.15×10^{17}	[28]
ClO ₂ (g)	2.89×10^5	6.46×10^{10}	1.87×10^{16}	Investigation
Polymeric aluminum chloride (g)	2.33×10^6	1.64×10^9	3.81×10^{15}	Investigation
Phosphide remover (g)	3.51×10^6	8.61×10^8	3.02×10^{15}	Investigation
Flocculant (g)	1.57×10^6	1.21×10^9	1.89×10^{15}	Investigation
Treatment water (g)	5.96×10^{12}	6.46×10^5	3.85×10^{18}	[38]

Table 2. ABR + CASS process energy analysis table.

Item	Basic Data	Emergy Conversion Rate	Solar Energy	Reference
Solar energy (J)	3.99×10^{13}	1	3.99×10^{13}	[20]
Wind energy (J)	1.25×10^{10}	6.63×10^2	8.29×10^{12}	[20]
Rainwater chemical energy (J)	5.13×10^{10}	1.54×10^4	7.90×10^{14}	[20]
Geothermal energy (J)	2.15×10^{10}	2.90×10^4	6.24×10^{14}	[20]
Hydroelectricity (J)	4.14×10^{12}	1.29×10^5	5.34×10^{17}	[37]
Labor service (CNY)	9.46×10^5	8.61×10^{11}	8.15×10^{17}	[28]
ClO ₂ (g)	3.00×10^5	6.46×10^{10}	1.94×10^{16}	Investigation
Polymeric aluminum chloride (g)	4.39×10^6	1.64×10^9	7.19×10^{15}	Investigation
Phosphide remover (g)	5.57×10^6	8.61×10^8	4.80×10^{15}	Investigation
Flocculant (g)	4.27×10^5	1.21×10^9	5.15×10^{14}	Investigation
Treatment water (g)	5.96×10^{12}	6.46×10^5	3.85×10^{18}	[38]

From the two process energy analysis tables, the main energy indicators of the two wastewater treatment processes were calculated and the results are shown in Table 3.

Table 3. Main energy indicators for the 2 processes.

Energy Indicators	ABR + A ² /O	ABR + CASS
Energy flow		
Renewable resource capacity values	3.61×10^{17}	5.36×10^{17}
Non-renewable resource capacity values	2.74×10^{16}	3.19×10^{16}
Purchase of energy	8.42×10^{17}	8.46×10^{17}
Yield value	3.85×10^{18}	3.85×10^{18}
Evaluation indicators		
Energy yield ratio	4.57	4.55
Environmental load factor	2.33	1.58
Indicators of sustainable development in terms of energy	1.96	2.88

The results of the comparative analysis of the emergy streams of the two wastewater treatment processes by type of resource input are shown in Figure 4.

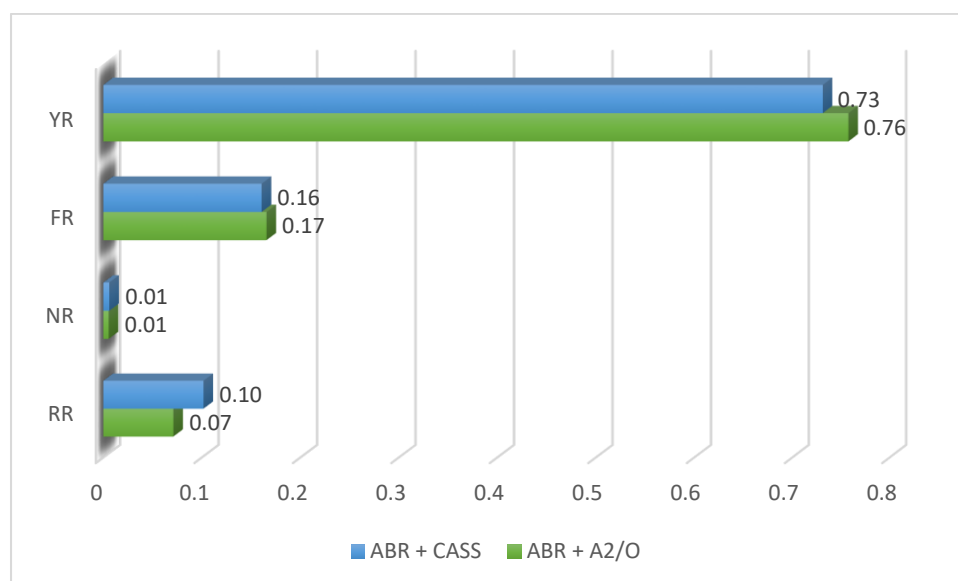


Figure 4. Comparative analysis of 2 process energy flows. RR: ratio of renewable resource energy flow to total energy flow, $RR = R/(R + N + F + Y)$; NR: ratio of non-renewable resource energy flow to total energy flow, $NR = N/(R + N + F + Y)$; FR: ratio of purchased energy flow to total energy flow, $FR = F/(R + N + F + Y)$; YR: ratio of yield energy flow to total energy flow, $YR = Y/(R + N + F + Y)$.

The results in Figure 4 show that for the two different wastewater treatment processes, the RR of the ABR + A2/O process was 0.031 lower than that of the ABR + CASS process; NR of the ABR + A2/O process was 0.001 lower than that of the ABR + CASS process; FR of the ABR + A2/O process was 0.005 higher than that of the ABR + CASS process; and YR of the ABR + A2/O process was 0.027 higher than that of the ABR + CASS process. Among the four indicators, RR and YR had the greatest effect on the sustainability of the wastewater treatment ecosystem, whereas NR and FR had little effect.

The energy indicators for the two wastewater treatment processes are shown in Figure 5.

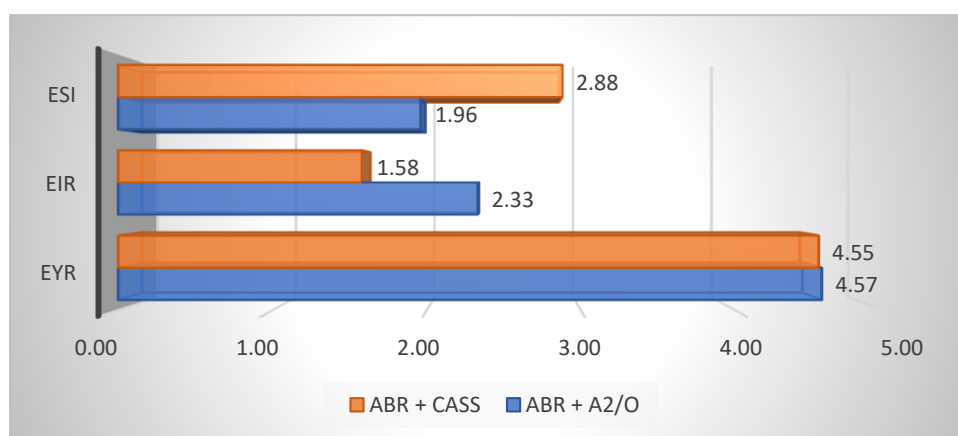


Figure 5. Results of energy analysis for the two processes.

The EYR reflects the economic efficiency of the system. As seen in Figure 5, the EYR of the ABR + CASS process was 4.55, slightly lower than that of the ABR + A2/O process. The ABR + A2/O process was better than the ABR + CASS process from the perspective of economic benefits and had stronger competitiveness. However, subsequent analysis of the main equipment and parameters of the two processes showed that under the same wastewater treatment capacity, the occupied area and civil engineering investment of the ABR + CASS process were lower than those of the ABR + A2/O process, and the economic

investment was lower. ELR reflects the pressure of the different wastewater treatment processes on the environment, and was lower in the ABR + CASS process than in the ABR + A2/O process (1.58 and 2.33, respectively); it thus creates lower pressure on the environment. The ESI was positively proportional to the EYR and inversely proportional to the ELR. The ABR + CASS process had a higher ESI than the ABR + A2/O process and thus would be more sustainable.

4. Discussion

During economic production and product life, a large amount of energy is consumed, the global greenhouse effect is accumulating, and the problem of global warming is becoming more and more serious [39]. From an energy consumption perspective, ways to effectively save energy, maximize energy use, and achieve sustainable development are important. Analysis of the sustainability of a wastewater treatment process to achieve sustainable development while harnessing the potential of economic operation is of great practical significance to promote and enhance energy conservation and consumption reduction in wastewater treatment plants.

Compared to other studies [12,15], the present study of wastewater treatment processes using the emergy analysis method considered the economic benefits of different treatment processes and their influence on the environment, and fully considered the natural resources used during wastewater treatment processes. This enabled a better evaluation of the relationship between wastewater treatment processes and environmental sustainability.

The results show that under the same sewage treatment capacity, the EYR and ELR of the ABR + A2/O process are higher and the ESI is relatively low. Therefore, from an economic benefit perspective, the ABR + A2/O process has stronger market competitiveness and a wastewater treatment model more in line with the economic interests of the market. However, from an environmental benefit perspective, the ABR + CASS process had higher sustainability and less pressure on the environment than the ABR + A2/O process. It was more in line with environmental interests. To better protect the deteriorating environment and increasingly scarce water resources, the ABR + CASS process is a better choice; however, its economic competitiveness is relatively poor, and the implementation of the ABR + CASS process needs increased policy support.

5. Conclusions

In this study, the economic benefit, ecological benefit, and sustainability of two wastewater treatment processes, ABR + A2/O and ABR + CASS, are evaluated by the emergy method. From the present study, the following insights were gained:

- (1) As an important part of urban infrastructure and a critical link in water pollution control, wastewater treatment is a socially beneficial project, which has significance for developing the national economy and environmental protection and resource reuse. Therefore, when selecting an appropriate wastewater treatment process, its economic benefits and influence on the environment from a sustainable development perspective should be considered.
- (2) The emergy method, when used for wastewater treatment process selection, uses a unified standard for measuring various resources and materials for inputs and outputs and can provide a reference for wastewater treatment plants to select a suitable treatment process for themselves by comparing the indicators.
- (3) The results indicate that the ABR + A2/O process had higher economic efficiency with the same wastewater treatment capacity; however, the ABR + CASS process was less damaging to the environment, had lower economic input and better sustainability and ecological economy, and more favorable economic policies can make it more widely promoted.

The present study had the following shortcomings: the research on improving the sustainability of wastewater treatment processes is not deep enough, and only considers the various input elements of the process operation, without considering the factors related

to the construction of the project, and lacks analysis of the relationship between various resources invested, reclaimed water reuse, sludge resource utilization and sustainability. Future studies will examine these aspects in greater detail.

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