Article

Environmental Sustainability Assessment of a New Sewage Treatment Plant in China Based on Infrastructure Construction and Operation Phases Emergy Analysis

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Abstract: Due to excessive resource consumption and pressing environmental issues of the sewage treatment industry, there is extensive attention in China. Given the unique craft production process in the sewage treatment system, a series of integral emergy indicators have been used to evaluate the environmental sustainability based on infrastructure construction and operation stage emergy analysis. Taking a new typical sewage treatment plant as an example, this paper performed a case study. The results illustrate that (1) the infrastructure construction process emergy (approximate 92.6%) is more critical than sewage treatment process emergy; (2) nonrenewable resource is the primary factor for the emergy analysis, followed by energy (23.5%) and purchased supply (7%); (3) cement, steel, and gravel have dominant impacts on the nonrenewable resource emergy; (4) the emergy sustainability index is 0.001101, which displays weak environmental sustainability; (5) the unit emergy value (UEV) of the new sewage treatment plant is 3.40×10^{12} sej/m³; (6) sensitivity analysis results of the hypothesis demonstrate that nonrenewable resources have significant fluctuations (6.903%) while, for the indicators, emergy sustainability index (ESI) (4.8072%) has the most significant impact; and (7) wastewater is a major contributor. In light of comprehensive discussions, two positive measures are proposed in order to ameliorate the environmental sustainability.

Keywords: sewage treatment industry; emergy analysis; indicators; sustainability

1. Introduction

As the world's largest developing country, there is massive sewage discharge every year in order to meet the needs of life and economic development in China. For example, 73.53 billion tons of wastewater was treated in 2015, such as 22.235 million tons of Chemical Oxygen Demand (COD) and 2.299 million tons of NH₃-N in China [1]. Total sewage treatment depends on the sewage treatment plant in China. As a manually designed system, sewage treatment plants need to consume a lot of resources and energy for sewage treatment; meanwhile, a large number of pollutants will be discharged, including exhaust gas, wastewater, and sludge waste [2]. Therefore, a series of resource, energy, and environmental issues will be generated; meanwhile, they can bring environmentally severe load and items for China, especially since China's economy has entered a period of rapid growth from the reform in the 1980s [3,4]. Under such a circumstance, it is necessary to evaluate the environmental sustainability in the sewage treatment industry.

Until now, several sustainable studies have been considered widely in view of different analysis perspectives for the sewage treatment industry. Many scholars have studied the relationship

between the environment in the sewage treatment industry using biological perspective analysis [5–8], lifecycle assessment (LCA) perspective [9], ecology models perspective [10], energy and economy performances [11], sewage treatment and water supply efficiency [12], chemical and physical angles [13,14], construction in the wastewater treatment plants [15], integrating wastewater treatment and incineration plants for energy-efficient study [16], sampling strategy for the sewage sludge survey [17], soil and the treatment of sewage treatment plant [18], and systematic assessment framework [19].

However, these studies have the following drawbacks: (1) for the isolated angles analysis, only one or some perspectives are chosen to demonstrate the interaction between environmental issues and the sewage treatment industry, resulting in a few unilateral conclusions; (2) ignorance of natural resources assessment leads to a negative impact on sustainability in the sewage treatment industry; (3) undifferentiated contribution degrees from different resource types could cause deviation inaccuracy to some extent; (4) there is a lack of a unified platform to evaluate sustainability in the sewage treatment industry, for example, an integrated method assessment should comprise resources, energy, labor, and others; and (5) some studies are unable to consider multiple pollutant emissions simultaneously, such as exhaust gas, wastewater, and solid waste. It will have a harmful effect on sustainability in the sewage treatment industry. In summary, the above studies cannot display the entire evaluated result in the sewage treatment industry.

Compared to the methodologies mentioned above, the emergy analysis (EMA) can improve these shortcomings and was put forward by Odum [20]. EMA could realize a unified platform to compare different types of input through unit emergy values (UEVs), involving natural resources, energy, labor, and environmental pollutants. Therefore, it can be selected to assess the various types of natural, artificial, and complex systems effectively. Meanwhile, natural resource efficiency, environmental issue, and sustainable degree can be illustrated clearly through a series of emergy indicators to finally obtain an authoritative assessment result for the targeted system. Sustainability assessments are hot topics based on emergy analysis (EMA) and contain a large quantity of different types related to agricultural studies [21,22], city assessments [23,24], green building field [25,26], production systems [27,28], national research [29], pollutant treatment [30], and traffic range [31].

Until now, several studies have been investigated to use the emergy approach in the sewage treatment industry. Yan et al. used an example of the Chinese sewage treatment industry to analyze the environmental sustainability issues based on the emergy method [32]. Based on the municipal sewage treatment ecosystem, XiaoHong et al. evaluated the sustainable degree by making use of the emergy method [33]. In view of four different wastewater treatment plants, sustainability and feasibility have been assessed using improved emergy indicators in the sewage treatment industry by F.L. da et al. [34]. Taking the wastewater treatment in Happy Farmer's Home as an example, Junsheng et al. confirmed several influencing factors on sustainability in China [35]. Natalia et al. conducted the emergy assessment in a wastewater treatment plant, which compared two management alternatives of biosolids [36]. The wastewater treatment system from a sugar factory in Sweden was assessed on the basis of the emergy theory [37]. Paolo et al. proposed a preliminary evaluation of a wastewater treatment plant system by considering the environmental costs of natural fluxes [38]. The ecological and economic effect of a decentralized sewage treatment plant was been surveyed by some authors [39]. Through a sewage treatment system before and after implementing a cleaner production measure, XiaoHong et al. executed two emergy evaluations to assess sustainability [40].

Several weak points can be found in these papers (shown in Table 1), including (1) a lack of infrastructure emergy consideration, in which, through the collation of current literature, the infrastructure emergy has not been taken into account in the sewage treatment system to assess environmental sustainability (shown in Table 1); (2) the use of an old emergy baseline, in which some articles use past emergy baselines rather than the latest emergy baseline; (3) the lack of pollutant evaluations, in which, in most items in Table 1, pollutants are not considered for the sewage treatment industry, such as exhaust gas, wastewater, and solid waste; for environmental sustainability in the

sewage treatment industry, it is necessary to assess the pollutant effect on the system; and (4) incomplete emergy indicators, in which only fundamental indicators had been computed in these papers and have no improved indexes based on infrastructure emergy, running emergy, and pollutant emergy for sewage treatment system evaluation. The above four disadvantages indicate that it is necessary to have a sustainable assessment for the sewage treatment industry based on emergy analysis (EMA) in China.

Table 1. Comparison of existing articles in the sewage treatment industry based on emergy.

Author	Year	Basic Data	Emergy Baseline	Emergy Analysis Angles			Country
				Infrastructure Emergy	Running Emergy	Pollutant Emergy	
Paolo et al.	2009	Old Plant	Old	×	√	×	Italy
XiaoHong et al.	2010	Old Plant	Old	×	√	√	China
XiaoHong et al.	2015	Old Plant	Old	×	√	×	China
Erik et al.	2017	A Pond	New	×	√	×	Sweden
Shuai et al.	2017	Old Plant	Old	×	√	√	China
Natalia et al.	2017	Grass system	Old	×	√	×	USA
Junsheng et al.	2017	A farm	New	×	√	√	China
Ling et al.	2017	Old Plant	New	×	√	×	China
Yan et al.	2018	Old Plant	New	×	√	√	China
This paper	Now	New plant	New	√	√	√	China

This paper aims to assess the environmental sustainability degree of the sewage treatment industry system through the EMA method. A new sewage treatment plant has been chosen for evaluation as an example, and all essential data can be obtained by investigation and calculation. Its contributions depend on several views, as follows: (1) considering the complete angles to assess the sewage treatment system, including infrastructure emergy, running emergy, and pollutant emergy; (2) establishing an improved and integral emergy analysis (EMA) and sustainable indicator group to evaluate the sewage treatment industry system; (3) calculating the unit emergy value of sewage treatment industry in China based on the environmental severity situation; and (4) proposing the corresponding strategies as reference for the factory manager.

Finally, the structure of the entire article is organized as follows: After the introduction section, Section 2 shows the methodology, including primary data and situation of the new sewage treatment plant, emergy analysis group, and industrial pollutant emergy details. Section 3 presents the results and discussion, containing main emergy calculated tables, emergy analysis, emergy indicators analysis, UEVs, sensitivity analysis, and industrial pollutant analysis. Section 4 discusses preventive strategies and positive suggestions. Finally, the main conclusions are summed up in Section 5.

2. Data and Methods

2.1. Basic Situation and Data of the New Sewage Treatment Plant

The new sewage treatment plant is in Shanghai city, along the Yangtze River in China. Shanghai is located between 120°52′ to 122°12′ east longitude and 30°40′ to 31°53′ north latitude and has a subtropical monsoon climate, with an annual temperature of 17.6 °C and a yearly wind speed of 3.25 m/s based on meteorological data of 2019 [41]. The land area is 6340.5 square kilometers. As China's largest and most developed city, Shanghai's gross domestic product was 474.6 billion US dollars [42].

The purpose of the new sewage treatment plant is to increase Shanghai's sewage treatment capacity. The new plant covers an area of 31.8 hectares, can process about 250,000 tons of sewage per day, and depends on 500 employees. As the core process, the A-O (Anaerobic-Oxic) wastewater treatment technology mainly uses the oxidation of microorganisms to degrade organic matter in wastewater and to achieve the effect of wastewater treatment. Total investments of the new sewage treatment plant contain 54.5 million US dollars of construction fee and 1.37 million US dollars of operation fee per year. The wastewater comes from municipal sewage and industrial wastewater of Shanghai, of which the details of wastewater has been shown in Tables 2–6, and the wastewater treatment technology

must meet the mandatory national standards [43]. In addition to the treated water, there are two byproducts, including dewatered sludge and exhaust gas pollutants. The dewatered sludge is sent to a landfill factory, and the amounts of exhaust gas pollutants are needed to be calculated. The treatment technology selected in the new plant represents the widely adopted type in the sewage treatment plant of China, which has universal applicability for China's sewage treatment plants.

Table 2. main building materials types.

No.	Item	Data	Unit	Source
1	Cement	5.44×10^7	kg	Investigation
2	Steel	2.83×10^7	kg	Investigation
3	Tap water	1450	M3	Investigation
4	Wood	5.79×10^5	kg	Investigation
5	Brick	1.97×10^6	kg	Investigation
6	Limestone	1.31×10^5	kg	Investigation
7	Gravel	2.03×10^7	kg	Investigation
8	Tile	7.36×10^5	kg	Investigation
9	Asphalt	1.40×10^5	kg	Investigation
10	Aluminum	1.14×10^6	kg	Investigation

Table 3. Auxiliary engineering costs.

No.	Project Types	Expenditure	Unit	Source
1	Scaffolding project	7,329,560	US \$	Investigation
2	Concrete formwork and bracket	16,784,840	US \$	Investigation
3	Equipment installation and disassembly	2,306,530	US \$	Investigation
4	Night construction	999,011	US \$	Investigation
5	Special season construction (Rainy and winter)	482,690	US \$	Investigation

Table 4. Comprehensive labor cost.

No.	Comprehensive Labor Type	Cost	Unit	Source
1	Construction Engineering Branch	917,390	US \$	Investigation
2	Installation Engineering Branch	213,873	US \$	Investigation
3	Decoration Engineering Branch	628,545	US \$	Investigation
4	Municipal Engineering Branch	136,947	US \$	Investigation

Table 5. Service and management fees for the government.

No.	Types	Fees	Unit	Source
1	Environmental protection fee	54,547.2	US \$	Investigation
2	Civilization Construction Fee	184,536.7	US \$	Investigation
3	Temporary facility fee	37,435.68	US \$	Investigation
4	Safety construction fee	86,615.89	US \$	Investigation
5	Engineering sewage charges	10,964.02	US \$	Investigation
6	Dangerous work accident insurance	43,999.70	US \$	Investigation

Table 6. Water-quality discharge from import and export concentration.

No.	Items	Inlet	Ref.	Outlet	Ref.	Unit
1	Chemical Oxygen Demand (COD)	120	Detected	50	GB 18918-2002	mg/L
2	Total Oxygen Demand (BOD)	40	Detected	10	GB 18918-2002	mg/L
3	Suspended Solids (SS)	130	Detected	10	GB 18918-2002	mg/L
4	P	2	Detected	0.5	GB 18918-2002	mg/L
5	N	30	Detected	15	GB 18918-2002	mg/L
6	NH3-N	25	Detected	5	GB 18918-2002	mg/L

2.1.1. Infrastructure Construction Process

In this building project, five sections need to be computed, including primary building materials, auxiliary engineering costs, energy consumption, labor cost, and government service charges. The specific data have been shown in Tables 2–5. The type of energy consumption is mainly electricity. According to statistics of the entire sewage treatment plant project, electricity costs are approximately 4.22×10^6 US dollars. All expenses have been converted into US dollars based on an exchange rate ($6.87 \text{ RMB} = 1 \text{ US\$}$).

2.1.2. Sewage Treatment Process

The Data of Sewage Treatment Plant

(1) Water-quality sample selection

According to the standard measurement [43], water samples from the plant inlet and outlet have been measured. The central monitoring indicators are Chemical Oxygen Demand (COD), Total Oxygen Demand (BOD), Suspended Solids (SS), total phosphorus, total nitrogen, ammonia nitrogen, etc. (shown in Table 6).

(2) Power operation system

The total capacity of the two main transformers is 16,000 KW in the new sewage treatment plant area, which can meet the power requirements of the entire sewage treatment plant area.

(3) Sludge treatment data

According to the statistics of the sewage treatment plant, the sludge volume is 55.8 tons per day (10 km transport distance by truck), and the incineration service fee of sludge treatment is \$18.76 per ton.

The Primary Process of the Sewage Treatment Plant

Core technologies of the sewage treatment plant contain a mechanical grid filtration system, grit chamber, first sedimentation tank, biotreatment, secondary sedimentation tank, tertiary sedimentation tank, and water treatment. The specific wastewater treatment process has been illustrated in Figure 1.

Figure 1. The wastewater treatment process in the sewage treatment plant.

2.2. Emergy Approach

2.2.1. Emergy Analysis (EmA)

As a comprehensive concept, emergy method comprises a direct part, the indirect part, the energy part, and labor and service. Its unit is solar emergy (sej), which was proposed by H.T. Odum [20] first. The most important superiority of emergy is that it can integrate environment resources, products, and services into a unified platform in order to assess the impact of sustainability [44].

By calculating the renewable resources, nonrenewable resources, economic investment, labor and service, and environmental emission consideration by transforming different physical units, including energy (J), mass (kg), and finance (\$), the sustainability of the sewage treatment plant system can be assessed and analyzed quantitatively [27].

The specific calculation of the emergy method involves the multiplication result by quantity and unit emergy values (UEVs). In more detail, mass, energy, and money can be converted into solar emergy (sej) by way of unit emergy values (UEVs) [45]. Therefore, unit emergy values (UEVs) are the pivotal item of the emergy method. In general, when emergy is computed, there are three types of UEVs, which are emergy/energy (sej/J), specific emergy (sej/g), and emergy/money (sej/\$) [32].

Before executing the emergy process, the selection of emergy baseline is a vital issue which can profoundly impact the accuracy of the sewage treatment plant sustainability. Emery baseline explains emergy values in the biosphere, consisting of solar, tidal, and geothermal energy. Because of constant correction by lots of researchers, five emergy baselines have been put forward until now, including 9.44×10^{24} sej/year [20], 9.26×10^{24} sej/year [46], 15.83×10^{24} sej/year [47], 15.2×10^{24} sej/year [48], and 12×10^{24} sej/year [49]. Compared to the five standards of emergy baseline, Brown et al. (2016) studied the newest baseline standard (12×10^{24} sej/year). In this paper, the latest emergy baseline (12×10^{24} sej/year) was adopted for the sustainable assessment of the sewage treatment plant.

2.2.2. Emery Diagram of the New Sewage Treatment Plant

In Figure 2, there are three sections to connect the new sewage treatment plant, including renewable energy, nonrenewable input, pollutant emissions, and qualified water. The upper part consists of sewage, electricity, transportation, and labor and service. The left part is the renewable energy, containing sunlight, rain (chemical potential), rain (geopotential), wind (kinetic energy), and geothermal heat. The right section is composed of pollutant emissions (exhaust gas and sludge waste) and qualified water.

Figure 2. The emergy diagram of the new sewage treatment plant.

2.2.3. Ecological Indicators

In this paper, there are a series of emergy-improved indicators to be adopted for the new sewage treatment plant assessment, as follows (shown in Table 7).

Table 7. All indicators of emergy for the new sewage treatment plant.

No.	Items	Index	Expression	Implication
1	Renewable energy emergy	R	R	Basic emergy input
2	Nonrenewable resource emergy	F	F	Basic emergy input
3	Purchased emergy	P	P	Basic emergy input
4	Wastewater treatment chemicals emergy	C	C	Basic emergy input
5	Labor and service emergy	L	L	Basic emergy input
6	Energy emergy	E	E	Basic emergy input
7	Transportation emergy	S	S	Basic emergy input
8	Pollutant emergy	Pe	Pe	Basic emergy input
9	Total emergy of the system	T	$R + F + P + C + L + E + S + Pe$	The total emergy of the system
10	Renewability rate	Rr	R/T	renewable proportion
11	Nonrenewability rate of local resource	Nr	F/T	local resource proportion
12	Nonrenewability rate of purchased resource	Np	P/T	Outside economic impact
13	Emergy personal density	Ed	T/person	Emergy per person
14	Emergy intensity	Ei	T/area	Emergy per area
15	Purchased emergy dependence level	PEDL	P/N	Competitiveness of the system
16	Pollutant environmental impact rate	PEIR	Pe/T	Pollutant degree
17	Emergy investment ratio	EIR	$P/(R + F)$	Economic development level
18	Environmental loading ratio	ELR	$(F + P + Pe)/R$	Environmental pressure
19	Emergy yield rate	EYR	$(R + F + P + Pe)/P$	Economic benefit
20	Emergy Sustainability Index	ESI	EYR/ELR	System sustainability

- (1) Renewability rate (Rr): it is a ratio between the renewable element and the total element. A higher renewability rate means a better ecological level;
- (2) Nonrenewability rate of local resource (Nr) displays the ratio within the local resource emergy and total emergy. Higher Nr demonstrates worse ecological degrees;
- (3) Nonrenewability rate of purchased resource (Np) reveals the proportion among purchased resource emergy and whole emergy. Lower Np shows a better sustainable level;
- (4) Emergy personal density (Ed) means the emergy per person, and the unit is sej/person. It reveals that the higher value represents better sustainability;
- (5) Emergy intensity (Ei) is defined as the emergy per unit area, which also enunciates the emergy production level;
- (6) Pollutant environmental impact rate (PEIR) represents the emergy proportion of pollutants in the entire assessment system. Large values indicate poor environmental sustainability;
- (7) Purchased emergy dependence level (PEDL) explains the competitiveness of the evaluated system. The smaller the PEDL is, the weaker the competitive strength is;
- (8) Emergy investment ratio (EIR): Emergy investment ratio delegates the proportion of purchased emergy to the sum of renewable emergy and nonrenewable emergy. EIR interprets the relationship between the individual economic input section and the natural input section [50]. The higher the EIR is, the stronger the economic development degree of the system is;
- (9) Emergy yield ratio (EYR): EYR can be computed in light of the total emergy section and imported emergy section, which shows an ability that can generate emergy. The higher the EYR is, the better the consequence of the new sewage treatment plant is. The higher input of purchased emergy could bring about lower EYR, revealing the competitive ability of the new sewage treatment plant. Several results can be referenced in Reference [51];
- (10) Environmental loading ratio (ELR): As the ratio of nonrenewable emergy and purchased emergy, EIR is defined, which can be used to elaborate the ecological load of the evaluated ecosystem, including non-resource emergy pressure, purchased emergy pressure, and others, such as exhaust emission and sludge waste, etc. Several studies have already conducted some standards for various environmental load degrees [52], including low values ($ELR < 2$), medium intensity ($3 < ELR < 10$), and high environmental load ($ELR > 10$);
- (11) Emergy sustainability index (ESI): ESI demonstrates the ratio between EYR and ELR. It expresses the far-reaching effect of the environment and economy for the evaluated system. Generally speaking, because of the literature in Reference [52], three standards were adopted to explain the sustainability status, which contain $ESI < 1$ (Unsustainable), $1 < ESI < 5$ (Medium situation), and $ESI > 5$ (Sustainable) in the long term;

- (12) Unit emergy values (UEVs) explains the emergy value of one unit of mass, energy, service, or money. UEVs mentions the efficiency of the evaluated system [53].

2.2.4. Sensitivity Analysis

Sensitivity analysis has a noticeable effect on the accuracy of emergy assessment result. To improve the efficiency, sensitivity analysis has been performed in this paper through the main contributor error changes of emergy calculation in the new sewage treatment plant. Generally speaking, the calculated formula of emergy can be shown by Equation (1):

$$E_m(i) = [(E + \varepsilon_e) \times i] \times [(T + \varepsilon_t) \times i] \quad (1)$$

where E_m is emergy; E represents energy (J), mess (kg), and economics (\$); T means unit emergy values (UEVs); ε_e signifies the error of E ; and ε_t shows the failure of T [54].

2.3. Industrial Pollutant Emergy Calculation

2.3.1. Exhaust Gas Emergy Calculation

Basic Emission Situation of Exhaust Gas

Seven processes mainly produce exhaust gas released by the new sewage treatment production. The process flow details can be found in Figure 1.

Based on the national mandatory standard [55], there are mainly three exhaust gases (power generation process) in the new sewage treatment plant, which are dust, sulfur dioxide (SO₂), and nitrogen oxides (NO_x). Human health and ecosystem sustainability can be affected by these exhaust emissions, specifically causing respiratory disease and disrupting the ecological balance aspect [56]. In order to achieve comprehensive considerations, the ecological service calculation and economic loss calculation should be investigated in this study. The untreated exhaust emissions contain 110 mg/m³ dust, 250 mg/m³ SO₂, and 300 mg/m³ NO_x in the new sewage treatment plant. After exhaust gas treatment (details are shown in Table 8), the corresponding data reduces to 35 µg/m³ dust, 50 µg/m³ SO₂, and 80 µg/m³ NO_x in view of the GB 3095-2012 standard (national mandatory standard in China) [57].

Table 8. DALY data of exhaust gas emission emissions in this article [32].

Name of Gas	Damage Impact on Human Health	DALY (a/Kg of Discharge)
Dust	respiratory	5.46×10^{-5}
SO ₂	respiratory	8.87×10^{-5}
NO _x	respiratory	3.75×10^{-4}

Note: DALY means disability adjusted life year (unit: a/Kg of Discharge).

Economic Loss Accounting

In this paper, the financial loss should be considered and computed, which was caused by exhaust emission of a new sewage treatment plant. According to the study of Bakshi (2002) [58], the human health effect has been adopted on the basis of the DALY (Table 8), and the calculated Equation (2) [59] has been displayed, as follows:

$$L = \sum W_i \times DALY_i \times \alpha \quad (2)$$

where L is the emergy loss that was produced by a human health effect and the unit is sej/a; I represents the gas type, containing dust, SO₂, and NO_x; W_i illustrates the exhaust amount; DALY means the impact element, a/kg emission; and α displays emergy value to humans per year and is 1.68×10^{16} sej/(a-person) based on the baseline 12.0×10^{24} sej/a [32].

Ecological Services Calculation

Ecological services calculation of exhaust gas reflects the negative impact of environmental issues. Therein, three air pollutants need to be calculated for emergy assessment of the new sewage treatment plant. For calculation of the ecological service, two steps need to advance. On the one hand, the exhaust gas amount must be computed based on Equation (3).

$$M_i = c \times \left(\frac{U_i \times 10^6}{s_i} \right) \quad (3)$$

where M_i shows the dilution air mass (Kg/a); i is the gas type, including dust, SO_2 , and NO_x ; c displays the air density (1.23 Kg/m^3); U_i represents the annual mass of air pollutants from the sewage treatment process, Kg/a; s_i is the acceptable concentration from agreed regulations, mg/m^3 ; and the three exhaust gases of acceptable concentration are dust (0.08 mg/m^3), SO_2 (0.02 mg/m^3), and NO_x (0.05 mg/m^3) [60]. On the other hand, the emergy of ecological service can be obtained on the basis of Equation (4).

$$R_{air,i} = 0.5 \times M_i \times v^2 \times T_w \quad (4)$$

where $R_{air,i}$ is the emergy of environmental service, sej/a; v is the local annual average wind speed (3.25 m/s); and T_w is the unit emergy value of wind ($1.86 \times 10^3 \text{ sej/J}$) according to baseline $12.0 \times 10^{24} \text{ sej/a}$ [32].

2.3.2. Wastewater Emergy Calculation

The emergy of wastewater in the new sewage treatment plant can be calculated as follows, including two procedures. Firstly, the freshwater consumption can be computed based on Equation (5), as follows:

$$Q_i = d \times \left(\frac{H_i \times 10^3}{e_i} \right) - M_{water} \quad (5)$$

where Q_i represents the freshwater consumption amount, Kg/a; i is 1 based on COD; d signifies the water density ($1.00 \times 10^3 \text{ Kg/m}^3$); H_i shows the annual amount of the water pollutant disposal from the new sewage treatment plant and the collected data is $2.5 \times 10^8 \text{ kg/a}$; e_i reveals the acceptable concentration (15 mg/L) based on national standard in China [61]; and M_{water} is the discharged wastewater in the new sewage treatment plant, and the value is $4.51 \times 10^3 \text{ m}^3/\text{a}$.

Secondly, the emergy of wastewater can be obtained from Equation (6).

$$E_{water,i} = Q_i \times T_n \quad (6)$$

where $E_{water,i}$ shows the emergy from the evaluated system (sej/a) and where T_n represents the unit emergy value of surface runoff in China. Here, it is $2.85 \times 10^7 \text{ sej/kg}$ based on the baseline of $12 \times 10^{24} \text{ sej/a}$ [49].

The wastewater treatment process of building new sewage treatment is displayed in Figure 1.

2.3.3. Sludge Waste Emergy Calculation

The consideration of sludge waste emergy is mainly concentrated on land occupation, which can be calculated based on Equation (7) [62]. Figure 3 shows the sludge treatment process of the new sewage treatment plant.

$$SLM = Z_{sludge} \times P_L \times \beta_L \quad (7)$$

where SLM represents the emergy of sludge waste for the new sewage treatment plant; Z_{sludge} is a total dry sludge ($2.5 \times 10^5 \text{ t/year}$), which has been dehydrated in the system; P_L shows the land requirement per unit sludge landfill and it is $2.85 \times 10^4 \text{ t/1 ha}$ [63]; and β_L is the unit emergy value of

local land, which is 0.8×10^{15} sej/ha based on the latest baseline (12.0×10^{24} sej/a). The details of the sludge treatment process have been revealed in Figure 3.

Figure 3. Sludge treatment process flow diagram of the new sewage treatment plant.

3. Results and Discussions

3.1. Emergy Calculated Table of the Sewage Treatment Plant in China

Emergy Calculated Table of the Sewage Treatment Plant in China are listed as followings:

All calculated emergy baseline is 12.00×10^{24} sej/yr [52] and the UEVs have been corrected in Table 9.

Table 9. Unit emergy values (UEVs) correction based on 12.00×10^{24} sej/year [64].

No.	Item	Raw UEVs	Emergy baseline(sej/a)	Ref.	Corrected UEVs	Unit
1	Sunlight	1	12.00×10^{24}	[65]	1	sej/j
2	Rain (chemical)	2.35×10^4	12.00×10^{24}	[65]	2.35×10^4	sej/j
3	Rain (geopotential)	1.31×10^4	12.00×10^{24}	[65]	1.31×10^4	sej/j
4	Wind (kinetic energy)	1.90×10^3	12.00×10^{24}	[65]	1.90×10^3	sej/j
5	Geothermal heat	4.37×10^4	12.00×10^{24}	[27]	4.37×10^4	sej/j
6	Gravel	1.42×10^{12}	12.00×10^{24}	[27]	1.42×10^{12}	sej/kg
7	Limestone	1.27×10^{12}	12.00×10^{24}	[27]	1.27×10^{12}	sej/kg
8	Cement	1.93×10^{12}	12.00×10^{24}	[27]	1.93×10^{12}	sej/kg
9	Steel	2.75×10^{12}	9.44×10^{24}	[66]	3.49×10^{12}	sej/kg
10	Wood	2.67×10^{12}	12.00×10^{24}	[67]	2.67×10^{12}	sej/kg
11	Brick	2.82×10^{12}	12.00×10^{24}	[68]	2.82×10^{12}	sej/kg
12	Tap water	9.03×10^{11}	12.00×10^{24}	[32]	9.03×10^{11}	sej/m ³
13	Tile	3.89×10^{12}	12.00×10^{24}	[68]	3.89×10^{12}	sej/kg
14	Asphalt	3.49×10^{12}	12.00×10^{24}	[67]	3.49×10^{12}	sej/kg
15	Aluminum	1.61×10^{13}	12.00×10^{24}	[68]	1.61×10^{13}	sej/kg
16	Polyaluminium chloride	3.37×10^6	12.00×10^{24}	[32]	3.37×10^6	sej/kg
17	Cl ₂ liquid	3.37×10^6	12.00×10^{24}	[32]	3.37×10^6	sej/kg
18	Polyacrylamide	3.37×10^6	12.00×10^{24}	[32]	3.37×10^6	sej/kg
19	Potassium permanganate	3.37×10^6	12.00×10^{24}	[32]	3.37×10^6	sej/kg
20	Labor & services	1.51×10^{10}	15.83×10^{24}	[69]	1.14×10^{10}	sej/\$
21	Electricity	4.50×10^5	12.00×10^{24}	[27]	4.50×10^5	sej/j

1—Renewable Energy calculation:

- (1) Solar energy calculation: Area of ceramic plant = 3.18×10^5 m²; insolation (Hubei Province, China) = 5.43×10^9 J/ m²/y [70]; albedo = 0.30 [70]; energy = (insolation) $\times$ (1 – albedo) $\times$ (area) =

- $(5.43 \times 10^9 \text{ J/m}^2/\text{y}) \times (1 - 0.30) \times (3.18 \times 10^5 \text{ m}^2) = 1.32 \times 10^8 \text{ J/y}$; UEV = 1.00 sej/J by definition; emergy of one year = $1.32 \times 10^8 \text{ J/y} \times 1 \text{ y} \times 1.00 \text{ sej/J} = 1.32 \times 10^8 \text{ sej}$;
- (2) Rain (chemical potential energy) calculation: Area of ceramic plant = $3.18 \times 10^5 \text{ m}^2$; rainfall (annual average, $n = 5$) = 0.68 m/y [70]; water density = 1.00 kg/m^3 ; evapotranspiration rate = 60% [69,71]; Gibbs free energy of water = $4.94 \times 10^3 \text{ J/kg}$; energy = (area) $\times$ (rainfall) $\times$ (evapotranspiration rate) $\times$ (water density) $\times$ (Gibbs free energy of water) = $(3.18 \times 10^5 \text{ m}^2) \times (0.68 \text{ m/y}) \times (60\%) \times (1 \times 10^3 \text{ kg/m}^3) \times (4.94 \times 10^3 \text{ J/kg}) = 6.41 \times 10^{11} \text{ J/y}$; UEV = $2.35 \times 10^4 \text{ sej/J}$ [65]; emergy of one year = $6.41 \times 10^{11} \text{ J/y} \times 1 \text{ y} \times 2.35 \times 10^4 \text{ sej/J} = 1.51 \times 10^{16} \text{ sej}$;
- (3) Rain (geopotential energy) calculation: Area of ceramic plant = $3.18 \times 10^5 \text{ m}^2$; rainfall (annual average, $n = 5$) = 0.68 m/y [72]; average elevation = 316 m [73]; water density = $1.00 \times 10^3 \text{ kg/m}^3$; runoff rate = 40.00% [69,71]; energy = (area) $\times$ (rainfall) $\times$ (runoff rate) $\times$ (water density) $\times$ (average elevation) $\times$ (gravity) = $(3.18 \times 10^5 \text{ m}^2) \times (0.71 \text{ m/y}) \times (40\%) \times (1 \times 10^3 \text{ kg/m}^3) \times (316 \text{ m}) \times (9.8 \text{ kg/m}^2) = 2.80 \times 10^{11} \text{ J/y}$; UEV = $2.79 \times 10^4 \text{ sej/J}$ [72]; emergy of one year = $2.80 \times 10^{11} \text{ J/y} \times 1 \text{ y} \times 2.79 \times 10^4 \text{ sej/J} = 7.81 \times 10^{15} \text{ sej}$;
- (4) Wind energy calculation: Area of ceramic plant = $3.18 \times 10^5 \text{ m}^2$; air density = 1.29 kg/m^3 ; wind velocity (annual average, $n = 2$) = 3.25 m/s [73]; velocity of geostrophic wind = 3.25 m/s (surface winds are considered as 0.6 of geostrophic wind [74]; drag coefficient = 1.00×10^{-3} [75]; energy = (area) $\times$ (air density) $\times$ (drag coefficient) $\times$ (velocity of geostrophic wind)³ = $(3.18 \times 10^5 \text{ m}^2) \times (1.29 \text{ kg/m}^3) \times (1.00 \times 10^{-3}) \times (3.25 \text{ m/s})^3 \times (3.15 \times 10^7 \text{ s/y}) = 4.43 \times 10^{11} \text{ J/y}$; UEV = $1.90 \times 10^3 \text{ sej/J}$ [65]; emergy of one year = $4.43 \times 10^{11} \text{ J/y} \times 1 \text{ y} \times 1.90 \times 10^3 \text{ sej/J} = 8.42 \times 10^{14} \text{ sej}$;
- (5) Geothermal heat calculation: Area of ceramic plant = $3.18 \times 10^5 \text{ m}^2$; heat flow (average) = $3.50 \times 10^{-2} \text{ J/m}^2/\text{s}$. energy = (area) $\times$ (heat flow) = $(3.18 \times 10^5 \text{ m}^2) \times (3.50 \times 10^{-2} \text{ J/m}^2/\text{s}) \times (3.15 \times 10^7 \text{ s/y}) = 3.51 \times 10^{11} \text{ J/y}$; UEV = $3.44 \times 10^4 \text{ sej/J}$ [72]; emergy of one year = $3.51 \times 10^{11} \text{ J/y} \times 1 \text{ y} \times 3.44 \times 10^4 \text{ sej/J} = 1.27 \times 10^{14} \text{ sej}$.

2—Nonrenewable resources:

The amount emergy: Cement = $5.44 \times 10^7 \times 1.93 \times 10^{12} = 1.05 \times 10^{20} \text{ sej}$;
 steel = $2.83 \times 10^7 \times 2.75 \times 10^{12} = 7.78 \times 10^{19} \text{ sej}$; limestone = $1.31 \times 10^5 \times 1.27 \times 10^{12} = 1.66 \times 10^{17} \text{ sej}$;
 gravel = $2.03 \times 10^7 \times 1.42 \times 10^{12} = 2.28 \times 10^{19} \text{ sej}$; wood = $5.79 \times 10^5 \times 2.67 \times 10^{12} = 1.55 \times 10^{18} \text{ sej}$;
 brick = $1.97 \times 10^6 \times 2.82 \times 10^{12} = 5.56 \times 10^{18} \text{ sej}$; tap water = $1.45 \times 10^6 \times 2.56 \times 10^{12} = 3.71 \times 10^{18} \text{ sej}$.

3—Purchased resources:

The amount emergy: Tile = $7.36 \times 10^5 \times 3.89 \times 10^{12} = 2.86 \times 10^{18} \text{ sej}$;
 asphalt = $1.40 \times 10^5 \times 3.49 \times 10^{12} = 4.89 \times 10^{17} \text{ sej}$; aluminum = $1.14 \times 10^6 \times 1.61 \times 10^{13} = 1.84 \times 10^{19} \text{ sej}$.

4—Wastewater treatment chemicals

The emergy calculations:

Polyaluminium chloride = $6.52 \times 10^9 \times 3.37 \times 10^6 = 2.20 \times 10^{16} \text{ sej}$;
 Cl_2 liquid = $3.86 \times 10^7 \times 3.37 \times 10^6 = 1.30 \times 10^{14} \text{ sej}$;
 polyacrylamide = $2.49 \times 10^7 \times 3.37 \times 10^6 = 8.39 \times 10^{13} \text{ sej}$;
 potassium permanganate = $3.04 \times 10^7 \times 3.37 \times 10^6 = 1.02 \times 10^{14} \text{ sej}$.

5—Labor and services:

(1) Auxiliary engineering labor costs:

Scaffolding project labor cost + concrete formwork and bracket labor cost + equipment installation and disassembly labor cost + night construction labor cost + special season construction (rain and winter) labor cost = $\$7,329,560 + \$16,784,840 + \$2,306,530 + \$999,011 + \$482,690 = \2.79×10^7 .

(2) Engineering Service fee:

Construction engineering service fee + installation engineering service fee + decoration engineering service fee + municipal engineering service fee = $\$917,390 + \$213,873 + \$628,545 + \$136,947 = \$1.89 \times 10^6$.

(3) Management service fees for the government:

Environmental protection fee + civilization construction fee + temporary facility fee + safety construction fee + engineering sewage charges + dangerous work accident insurance = \$54,547.2 + \$184,536.7 + \$37,435.68 + \$86,615.89 + \$43,999.70 = \$4.18 × 10⁵.

(4) The amount of emergy of labor and services: (\$2.79 × 10⁷ + \$1.89 × 10⁶ + \$4.18 × 10⁵) × 1.14 × 10¹⁰ = 3.44 × 10¹⁷ sej.

6—Energy:

Construction electricity per kWh in China = 1 kwh/REM × 0.687 = 0.687 kwh/\$.

- (1) Infrastructure electricity of the new sewage treatment plant: (4.22 × 10⁶\$/0.687 kwh/\$) × 3.6 × 10⁶j = 2.21 × 10¹³j;
- (2) annual electricity operation cost of sewage treatment plant: 16,000 kwh × 24 h × 365 d × 3.6 × 10⁶j = 1.40 × 10¹⁴j;
- (3) the amount of emergy of electricity = (2.21 × 10¹³ + 1.40 × 10¹⁴) × 4.50 × 10⁵ = 7.29 × 10¹⁹ sej.

7—Transportation:

Transportation emergy of annual sludge treatment = (55.8 tons × 10 km × 365d) × (7.61 × 10¹¹) = 1.55 × 10¹⁷ sej.

8—Industrial pollutant emissions:

(1) Exhaust gas emergy of the new sewage treatment plant

- (1) The economic loss emergy:

$$L_{Dust} = \sum W_i \times DALY_i \times \alpha = (35 \times 10^{-9}) \times (3.75 \times 10^{-4}) \times (1.68 \times 10^{16}) \times 365 \times (2.5 \times 10^5) = 2.01 \times 10^{13} \text{ sej}$$

$$L_{SO_2} = \sum W_i \times DALY_i \times \alpha = (50 \times 10^{-9}) \times (5.46 \times 10^{-5}) \times (1.68 \times 10^{16}) \times 365 \times (2.5 \times 10^5) = 4.18 \times 10^{13} \text{ sej}$$

$$L_{NO_X} = \sum W_i \times DALY_i \times \alpha = (80 \times 10^{-9}) \times (8.87 \times 10^{-4}) \times (1.68 \times 10^{16}) \times 365 \times (2.5 \times 10^5) = 1.09 \times 10^{14} \text{ sej}$$

- (2) The ecological services emergy:

$$M_{Dust} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(35 \times 10^{-9}) \times (1.0 \times 10^6)}{0.08} \right] \times (2.5 \times 10^5) \times 365 = 4.93 \times 10^7 \text{ kg/a}$$

$$M_{SO_2} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(50 \times 10^{-9}) \times (1.0 \times 10^6)}{0.02} \right] \times (2.5 \times 10^5) \times 365 = 2.81 \times 10^8 \text{ kg/a}$$

$$M_{NO_X} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(80 \times 10^{-9}) \times (1.0 \times 10^6)}{0.05} \right] \times (2.5 \times 10^5) \times 365 = 1.79 \times 10^8 \text{ kg/a}$$

$$R_{Dust} = 0.5 \times M_{Dust} \times v^2 \times T_w = 0.5 \times (4.93 \times 10^7) \times 3.25^2 \times (1.86 \times 10^3) = 4.84 \times 10^{12} \text{ sej}$$

$$R_{SO_2} = 0.5 \times M_{SO_2} \times v^2 \times T_w = 0.5 \times (2.81 \times 10^8) \times 3.25^2 \times (1.86 \times 10^3) = 2.76 \times 10^{12} \text{ sej}$$

$$R_{NO_X} = 0.5 \times M_{NO_X} \times v^2 \times T_w = 0.5 \times (1.79 \times 10^8) \times 3.25^2 \times (1.86 \times 10^3) = 1.76 \times 10^{12} \text{ sej}$$

- (3) The sum of economic loss emergy and ecological services emergy:

$$Emergy_{dust} = (2.01 \times 10^{13}) + (4.84 \times 10^{12}) = 2.49 \times 10^{13} \text{ sej}$$

$$Emergy_{SO_2} = (4.18 \times 10^{13}) + (2.76 \times 10^{12}) = 4.46 \times 10^{13} \text{ sej}$$

$$Emergy_{NO_X} = (1.09 \times 10^{14}) + (1.76 \times 10^{12}) = 1.11 \times 10^{14} \text{ sej}$$

(2) Wastewater emergy of the new Sewage Treatment Plant

$$Q_{Wastewater} = [d \times \left(\frac{H_i \times 10^3}{e_i} \right) - M_{water}] \times T_n = [1.0 \times 10^3 \times \left(\frac{2.5 \times 10^5}{0.015} \right) - 4.51 \times 10^6] \times 2.85 \times 10^7 = 4.75 \times 10^{17} \text{ sej}$$

(3) Sludge waste emergy of the new Sewage Treatment Plant

$$SLM_{solid-waste} = Z_{sludge} \times P_L \times \beta_L = (55.8 \times 365) \times [1 / (2.85 \times 10^4)] \times (8.0 \times 10^{14}) = 5.72 \times 10^{14} \text{ sej}$$

$$\text{Incineration service energy of sludge} = (18.76 \text{ \$/t}) \times 55.8 \text{ t} \times (1.14 \times 10^{10}) = 1.19 \times 10^{13}$$

$$\text{The sum of Sludge waste energy} = (5.72 \times 10^{14} \text{ sej}) + (1.19 \times 10^{13}) = 5.84 \times 10^{14} \text{ sej}$$

3.2. Emery Analysis (EmA)

Table 10 is a comprehensive evaluated platform which integrates the infrastructure construction process energy calculation and the sewage treatment process energy calculation. There are eight sections for calculating emery to assess the sustainability in the evaluated system, including renewable energy, nonrenewable resource, purchased resource, wastewater treatment chemicals, labor and service, energy, transportation, and industrial pollutant emissions.

Table 10. Comprehensive emery calculation form of the sewage treatment plant.

Name	Formula Ratio	Basic Data	Unit	Ref. for the Data	UEVs sej/unit	Ref. for the UEVs	Emery (sej)	%
1—Renewable Energy (See note 1 for the specific calculation process)							2.39×10^{16}	0.01
Sunlight		1.32×10^8	J/y	Calculated	1	[65]	1.32×10^8	0.00
Rain (chemical potential)		6.41×10^{11}	J/y	Calculated	2.35×10^4	[65]	1.51×10^{16}	0.01
Rain (geo potential)		2.80×10^{11}	J/y	Calculated	2.79×10^4	[65]	7.81×10^{15}	0.00
Wind (kinetic energy)		4.43×10^{11}	J/y	Calculated	1.90×10^3	[65]	8.42×10^{14}	0.00
Geothermal heat		3.51×10^{11}	J/y	Calculated	3.44×10^4	[27]	1.27×10^{14}	0.00
2—Nonrenewable resources (For construction infrastructure of the plant)							2.14×10^{20}	69.1
Cement		5.44×10^7	kg	Collected	1.93×10^{12}	[27]	1.05×10^{20}	33.9
Steel		2.83×10^7	kg	Collected	2.75×10^{12}	[66]	7.78×10^{19}	25.1
Gravel		2.03×10^7	kg	Collected	1.42×10^{12}	[27]	2.28×10^{19}	7.36
Brick		1.97×10^6	kg	Collected	2.82×10^{12}	[68]	5.56×10^{18}	1.79
Wood		5.79×10^5	kg	Collected	2.67×10^{12}	[67]	1.55×10^{18}	0.50
Tap water		1.45×10^6	M3	Collected	9.03×10^{11}	[32]	1.31×10^{18}	0.42
Limestone		1.31×10^5	kg	Collected	1.27×10^{12}	[27]	1.66×10^{17}	0.05
3—Purchased resources (For construction infrastructure of the sewage plant)							2.17×10^{19}	7.00
Aluminum		1.14×10^6	kg	Collected	1.61×10^{13}	[68]	1.84×10^{19}	5.94
Tile		7.36×10^5	kg	Collected	3.89×10^{12}	[68]	2.86×10^{18}	0.92
Asphalt		1.40×10^5	kg	Collected	3.49×10^{12}	[67]	4.89×10^{17}	0.16
4—Wastewater treatment chemicals (For operational requirements of the plant)							2.23×10^{16}	0.01
Polyaluminium chloride		6.52×10^9	kg	Collected	3.37×10^6	[32]	2.20×10^{16}	0.01
Cl ₂ liquid		3.86×10^7	kg	Collected	3.37×10^6	[32]	1.30×10^{14}	0.00
Polyacrylamide		2.49×10^7	kg	Collected	3.37×10^6	[32]	8.39×10^{13}	0.00
Potassium permanganate		3.04×10^7	kg	Collected	3.37×10^6	[32]	1.02×10^{14}	0.00
5—Labor and services (The sum of construction infrastructure and operational)							3.44×10^{17}	0.11
Labor and services		3.02×10^7	\$	Collected	1.14×10^{10}	[69]	3.44×10^{17}	0.11
6—Energy (The sum of construction infrastructure and operational requirements)							7.29×10^{19}	23.5
Electricity		1.62×10^{14}	J	Collected	4.50×10^5	[27]	7.29×10^{19}	23.5
7—Transportation (For sludge transportation of the plant)							1.55×10^{17}	0.05
Transportation (truck)		2.04×10^5	t-km	Collected	7.61×10^{11}	[27]	1.55×10^{17}	0.05
8—Industrial pollutant emissions (For operational pollutants of the plant)							4.76×10^{17}	0.15
Exhaust gas		Dust	35 µg/m ³	[60]	~	See note 8-1	2.49×10^{13}	0.00
		SO ₂	50 µg/m ³	[60]	~	See note 8-1	4.46×10^{13}	0.00
		NO _x	80 µg/m ³	[60]	~	See note 8-1	1.11×10^{14}	0.00
Wastewater		~	~	~	~	See note 8-2	4.75×10^{17}	0.15
Sludge waste		~	~	~	~	See note 8-3	5.84×10^{14}	0.00
Total		~	~	~	~	~	3.10×10^{20}	100
UEVs		UEVs = 3.40×10^{12} sej/m ³ for the new sewage treatment plant						

Based on the emery calculations of nonrenewable resources and purchased resources, the infrastructure construction process emery (at least 92.6% of the entire emery in the new sewage treatment plant) is more critical than the sewage treatment process emery and has a self-evident superiority.

According to the proportion of emergy in Table 10, nonrenewable resource is the primary contributor, which accounts for 69.1% of the total emergy amount, followed by energy (23.5%), purchased resource (7%), industrial pollutant emissions (0.15%), labor and services (0.11%), transportation (0.05%), wastewater treatment chemicals (0.01%), and renewable energy (0.01%).

From Table 10, the nonrenewable resource has the dominant effect for the evaluated result, which is made up of cement (33.9%), steel (25.1%), gravel (7.36%), brick (1.79%), wood (0.50%), tap water (0.42%), and limestone (0.05%). Therein, the cement, steel, and gravel have dominant impacts on the nonrenewable resource emergy, and the proportions are 66.36% of the total emergy and 92.19% of the nonrenewable resource emergy. The energy holds a secondary influence for the complete result, and the main energy type is electricity. The purchased resource is the third most influential factor, and it is composed of aluminum (5.94%), tile (0.92%), and asphalt (0.16%). Among them, aluminum is the crucial part and has an 84.6% ratio for the entire purchased resource emergy.

Industrial pollutant emission consists of three factors, involving exhaust gas (0.00%), wastewater (0.15%), and solid waste (0.00%). Therein, the wastewater possesses the pivotal consequence in light of industrial pollutant emission emergy, far greater than exhaust gas and wastewater. The exhaust gas is a three-part composition, including dust, SO₂, and NO_x, which has hardly any impact on the emergy assessment.

Labor and service (0.11%) plays a small role in the sustainability of the new sewage treatment plant based on real productivity of China.

Finally, transportation (0.05%), wastewater treatment chemicals (0.01%), renewable energy (0.01%), and renewable energy (0.00%) have small effects on the entire evaluated system of the new sewage treatment plant.

3.3. Emergy Indicators Analysis

All the ecological indicators of the new sewage treatment plant are displayed in Table 11.

Table 11. Calculated results of ecological indicators.

No.	Items	Index	Expression	Results
1	Renewable energy emergy	R	R	2.39×10^{16} sej
2	Nonrenewable resource emergy	F	F	2.14×10^{20} sej
3	Purchased emergy	P	P	2.17×10^{19} sej
4	Wastewater treatment chemicals emergy	C	C	2.23×10^{16} sej
5	Labor and service emergy	L	L	3.44×10^{17} sej
6	Energy emergy	E	E	7.29×10^{19} sej
7	Transportation emergy	S	S	1.55×10^{17} sej
8	Pollutant emergy	Pe	Pe	4.76×10^{17} sej
9	Total emergy of the system	T	$R + F + P + C + L + E + S + Pe$	3.10×10^{20} sej
10	Renewability rate	Rr	R/T	0.000077
11	Non-renewability rate of local resource	Nr	F/T	0.690323
12	Non-renewability rate of purchased resource	Np	P/T	0.070000
13	Emergy personal density	Ed	T/person	6.20×10^{17} sej/person
14	Emergy intensity	Ei	T/area	9.75×10^{17} sej/m ²
15	Purchased emergy dependence level	PEDL	P/F	0.101402
16	Pollutant environmental impact rate	PEIR	Pe/T	0.001535
17	Emergy investment ratio	EIR	$P/(R + F)$	0.101391
18	Environmental loading ratio	ELR	$(F + P + Pe)/R$	9881.841
19	Emergy yield rate	EYR	$(R + F + P + Pe)/P$	10.88479
20	Emergy Sustainability Index	ESI	EYR/ELR	0.001101

- (1) The renewability rate (Rr) is 0.000077, which demonstrates the weak sustainability and ecological level.
- (2) Nonrenewability rate of local resource (Nr) reveals the ratio (0.690323), and the result illustrates the excessive local resource input and has caused considerable pressure on the local environment.
- (3) Nonrenewability rate of purchased resource (Np) is 0.07. The result shows that the entire evaluation process requires considerable economic resource input, which hurts a sustainable level.
- (4) Emergy personal density (Ed) is 6.20×10^{17} sej/person, which represents the relatively high degree of automated production in the new sewage treatment plant.

- (5) Emergy intensity (E_i) is 9.75×10^{17} sej/m², and it enunciates the better effect of land utilization to a certain degree.
- (6) Purchased emergy dependence level (PEDL) is 0.101402, which explains the competitiveness of the evaluated system. Because of the lower economic input, the competitive strength is unqualified and needs to be improved.
- (7) Pollutant environmental impact rate (PEIR) is 0.001535. It decides the poor influence on the whole system and could generate real sustainability.
- (8) Emergy investment ratio (EIR) is 0.101391, which interprets low investment in the system. Compared to the natural input section, the proportion of the individual economic input section needs to be enhanced to improve the sustainable degree.
- (9) The environmental loading ratio (ELR) is 9881.841, which shows the excessive pressure on the system. According to several standards of the study [55], the high environmental load (>5) has been displayed and should carefully consider some measures to decrease the ELR. Through the integrated infrastructure construction process and sewage treatment process, the system has severe stress and should consider mitigation carefully.
- (10) Emergy yield ratio (EYR) is 10.88479, representing the competitive ability of the evaluated system. It needs to balance the relationship between the total emergy section and purchased emergy for sustainability of the new sewage treatment plant.
- (11) The emergy sustainability index (ESI) is 0.001101. It expresses the weak comprehensive effect of the environment on the evaluated system. Based on the literature in Reference [55], the ESI of the new sewage treatment plant has an unsustainable status (<1) in the long term.

3.4. Unit Emergy Values (UEVs)

According to the statistics in Table 12, some articles have been investigated for the UEVs of sewage treatment plants in China. In the last five years, there are two papers related to UEVs of sewage treatment in China, which are XiaoHong et al.; 2015 (6.79×10^{11} sej/m³) and Yan et al., 2018 (9.03×10^{11} sej/m³). In order to compare the UEVs, the unified emergy baseline should be adopted, and in view of 12.00×10^{24} sej/y, 6.79×10^{11} sej/m³ can be corrected to 5.15×10^{11} sej/m³. Based on running emergy calculations of an old sewage treatment plant, Xiaohong (2015) calculated the UEVs (5.15×10^{11} sej/m³), which is smaller than 9.03×10^{11} sej/m³, on the basis of running emergy calculation and pollutant emergy calculation by Yan (2018).

Table 12. Comparison of existing articles on unit emergy values (UEVs) in China.

Author	Basic Data	Emergy Baseline (Sej/y)	UEVs	Unit	Emergy Analysis Angles			Country
					Infrastructure Emergy	Running Emergy	Pollutant Emergy	
XiaoHong et al., 2015	An old Plant	15.83×10^{24}	6.79×10^{11}	Sej/m ³	×	√	×	China
Yan et al., 2018	An old Plant	12.00×10^{24}	9.03×10^{11}	Sej/m ³	×	√	√	China
This paper	A new plant	12.00×10^{24}	3.40×10^{12}	Sej/m ³	√	√	√	China

In this paper, the UEVs (3.40×10^{12} sej/m³) of a new sewage treatment plant have been computed based on infrastructure emergy, running emergy, and pollutant emergy. Higher UEVs illustrate the worst sustainable level, and it demonstrates the low efficiency of the new sewage treatment plant system due to the infrastructure emergy input. Several studies have been executed to enhance the environmental sustainability of a similar system by making better UEVs.

Energy-saving strategies have been considered carefully by Lemos et al., (2013) [76] and Amores et al., (2013) [77] and can reduce the UEVs of the sewage treatment plant. XiaoHong et al. (2018) has suggested sewage treatment process optimization [40] in order to improve the water treatment efficiency and to lower the UEVs of the sewage treatment plant. Moreover, several comprehensive measures can also be conducted to enhance the UEVs of the sewage treatment plant, including

replacement of renewable materials [78], adjustment of industrial structure [79], and development of renewable energy [80,81].

3.5. Sensitivity Analysis

As shown in Table 10, the total emergy input is divided into eight sections, involving renewable energy, nonrenewable resource, purchased resource, wastewater treatment chemicals, labor and service, energy, transportation, and industrial pollutant emissions. Based on Table 13, there are three main contributors to the entire emergy of the new sewage treatment plant, which are a nonrenewable resource, energy, and purchased resource. It is necessary to run a sensitivity analysis for these three parts in Table 10. Here, a hypothesis is used to verify the sensitivity analysis: each of the three items changes by 10%, and other input items are forced to remain constant to test the changes of total emergy and indicators.

Table 13. The sensitivity changes in three main contributors of the evaluated system.

No.	Items	Former (sej)	Latter (sej)	Changes (%)
1	Nonrenewable resources	2.14×10^{20}	2.35×10^{20}	6.903%
2	Purchased resources	2.17×10^{19}	2.39×10^{19}	0.700%
3	Energy	7.29×10^{19}	8.02×10^{19}	2.352%

The sensitivity analysis of all details has been calculated in the paper, which has been displayed in Table 14 and in Figures 4 and 5.

Table 14. The indicators changes between former and latter.

No.	Items	Index	Former	Latter	Unit
1	Renewability rate	Rr	0.000077	0.000070	~
2	Nonrenewability rate of local resource	Nr	0.690323	0.689150	~
3	Nonrenewability rate of purchased resource	Np	0.070000	0.070088	~
4	Emergy personal density	Ed	6.20×10^{17}	6.82×10^{17}	sej/per
5	Emergy intensity	Ei	9.75×10^{14}	1.07×10^{15}	sej/m ²
6	Purchased emergy dependence level	PEDL	0.101402	0.101702	~
7	Pollutant environmental impact rate	PEIR	0.001535	0.001396	~
8	Emergy investment ratio	EIR	0.101391	0.101692	~
9	Environmental loading ratio	ELR	9881.841	10852.55	~
10	Emergy yield rate	EYR	10.88479	10.85355	~
11	Emergy Sustainability Index	ESI	0.001101	0.001000	~

Figure 4. Comparison of all indicators between former and latter.

Figure 5. The indicator changes between former and latter.

Table 13 demonstrates sensitivity analysis situations in the hypothesis. Within -10% changes in the three sections, it can be concluded that the nonrenewable resources have the most significant fluctuation (6.903%), followed by energy (2.352%) and purchased resources (0.700%). The reason for the tendency is that nonrenewable resources play a significant consequence, more critical than others, and this can be known from the energy contribution ratio, accounting for 69.1% of total energy in the evaluated system. The same explanations can be for purchased resources and energy. The higher the energy ratio, the greater the sensitivity results. This result explains that the staple energy contributor exerts the foremost impact on sensitivity analysis.

Sensitivity analysis of all indicators has been illustrated in Figures 4 and 5 for Rr (4.7619%), Nr (0.0850%), Np (−0.0628%), Ed (−4.7619%), ELR (−4.6816%), PEDL (−0.1477%), PEIR (4.7424%), EIR (−0.1482%), ELR (−4.6816%), EYR (0.1437%), ESI (4.8072%). It is found that ESI (4.8072%) has the biggest impact, followed by Rr (4.7619%), Ed (−4.7619%), PEIR (4.7424%), ELR (−4.6816%), and ELR (−4.6816%).

3.6. Industrial Pollutant Analysis

In the new sewage treatment plant system, there are three main types of pollutant emissions in Table 8, including exhaust gas, wastewater, and solid waste. Specific details have been displayed in the note of Table 10. According to Table 10, wastewater is the major contributor and accounts for 0.15% of the entire energy and almost 100% of the industrial pollutant energy. Therein, exhaust gas and wastewater have virtually no impact on the system. It is clear that sludge treatment technology (Figure 3) is feasible and has a better effect than wastewater treatment technology (Figure 1).

4. Strategies and Suggestions

Based on the aforementioned results, several strategies and recommendations have been provided to make better sustainable and comprehensive performance.

4.1. Improving the Proportion of Renewable Energy Use

Unreasonable energy structures should be responsible for the negative effect on the sustainability of the new sewage treatment plant in China. The small percentage of renewable energy leads to low sustainability for the evaluated system. To adjust the energy structure, several new renewable energy types should be adopted in this paper, including solar power, hydropower, and wind power, which are the familiar sources of renewable energy in China. However, a few weak points obstruct their usages as renewable energy sources, such as enormous investment, professional and technical barriers, and geographical conditions. For example, financial subsidies and favorable tax policies

should be considered carefully to improve the applied proportion of clean energy. Based on the development status, many researchers have performed related studies involving solar power [82,83], hydropower [84,85], and wind power [86,87].

4.2. Recycling Material Replacement

Due to the excessive dependence on nonrenewable resources in the new sewage treatment plant, there is a substantial environmental load for the evaluated system. Taking cement as an example, it accounts for the most significant consumption (33.9% of total energy in the system). It hampers the sustainable improvement of the new sewage treatment plant in this study. Related material substitution is currently proven effective, primarily focusing on industrial waste and byproducts, like industrial slag, construction waste, metallurgical waste, mining waste, fuel waste, and chemical waste, etc.

Currently, many scholars have done some research on material substitution for cement so as to improve sustainability [88,89]. Gonçalves et al. (2020) used the recycled concrete aggregate and reactive magnesium oxide to replace the cement material, which can promote the mechanical and environmental performance. In view of the new treatment technology, the wet-milling concrete slurry waste can be adopted to substitute cement according to the study of Xingyang et al. (2020).

5. Conclusions

Based on emergy methodology, the sustainable assessment of China's new sewage treatment factory has been investigated, calculated, and analyzed in this paper. The main conclusions are summarized as follows.

According to the emergy calculations of nonrenewable resources and purchased resources, the infrastructure construction process emergy (at least 92.6% of the entire emergy in the new sewage treatment plant) is more critical than the sewage treatment process emergy and has a self-evident superiority.

Emergy contributor orders: nonrenewable resource accounts for 69.1% of the total emergy amount, followed by energy (23.5%), purchased resource (7%), industrial pollutant emissions (0.15%), labor and services (0.11%), transportation (0.05%), wastewater treatment chemicals (0.01%), and renewable energy (0.01%).

The cement, steel, and gravel have dominant impacts on the nonrenewable resource emergy, and the proportions are 66.36% of the total emergy and 92.19% of the nonrenewable resource emergy. The energy holds a secondary influence on the complete result, and the primary energy type is electricity. The purchased resource is the third most influential factor.

A series of indicators are 0.000077 (renewability rate); 0.690323 (nonrenewability rate of local resource); 0.101402 (purchased emergy dependence level); 0.001535 (pollutant environmental impact rate); 0.101391 (emergy investment ratio); 10.88479 (emergy yield ratio); 9881.841 (environmental loading ratio); and 0.001101 (emergy sustainability index). All indicator groups illustrate poor sustainability in the new sewage treatment plant and need to adopt some measures to improve the state.

In this paper, the UEVs (3.40×10^{12} sej/m³) of a new sewage treatment plant have been computed based on infrastructure emergy, running emergy, and pollutant emergy. Higher UEVs illustrate the worst sustainable level, and it demonstrates the low efficiency of the new sewage treatment plant system due to the infrastructure emergy input.

A hypothesis is used to verify the sensitivity analysis. The results show that the nonrenewable resources have the most significant fluctuation (6.903%), followed by energy (2.352%) and purchased resources (0.700%). For the indicators, ESI (4.8072%) has the most significant impact, followed by Rr (4.7619%), Ed (−4.7619%), PEIR (4.7424%), ELR (−4.6816%), and ELR (−4.6816%).

The wastewater is the major contributor and accounts for 0.15% of the entire emergy and almost 100% of the industrial pollutant emergy. Therein, exhaust gas and wastewater have practically no impact on the system.

To sum up, the new sewage treatment plant holds an excessive environmental loading ratio and poor energy sustainability index. Hence, it cannot maintain sustainable growth; however, some positive measures are considered and implemented so as to ameliorate the sustainability, including enhancing the proportion of renewable energy input and recycling material replacement.

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