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Study on the Coupling Relationship between Carbon Emission from Sewage Treatment and Economic Development in Industrial Parks

Xiaoping Liu [1,2,3], Shengdong Cheng [1,2], Zhanbin Li [1,2,*], Peng Li [1,2], Tian Wang [1,2,*], Xingyue Guo [1], Ziyao Miao [3], Naichang Zhang [4] and Yongxiang Cao [4]

[1] State Key Laboratory of Eco-Hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an 710048, China
[2] Key Laboratory of National Forestry Administration on Ecological Hydrology and Disaster Prevention in Arid Regions, Xi'an University of Technology, Xi'an 710048, China
[3] Yulin High-Tech Zone Yuheng No. 1 Industrial Sewage Treatment Company, Yulin Coal Chemical Waste Resource Utilization and Low Carbon Environmental Protection Engineering Technology Research, Yulin 719000, China
[4] Northwest Engineering Corporation Limited, Xi'an 710065, China
* Correspondence: zhanbinli@126.com (Z.L.); t.wang@xaut.edu.cn (T.W.)

Abstract: Sewage treatment carbon emissions are one of the notable sources of total carbon emission in industrial parks. In order to explore the evolutionary characteristics of sewage treatment carbon emission in industrial parks and its coupling relationship with industrial economic development, based on the quarterly sewage quality monitoring data and regional economic development data of an energy and chemical industry park in Northern Shaanxi from 2016 to 2020, this paper analyzes the evolutionary characteristics of sewage treatment carbon emissions and the coupling relationship between economic development in the industrial parks by using the Intergovernmental Panel on Climate Change carbon emission accounting method and the coupling coordination degree model. The results show that the total carbon emission of sewage treatment in the industrial parks is increasing year by year, and the indirect carbon emissions occupy the dominant position. In 2020, the direct and indirect carbon emissions in the sewage treatment process accounted for 2.4% and 97.6% of the total carbon emission, respectively. It was found that the coupling and coordination relationship between sewage treatment carbon emissions and the economy has experienced the transformation process of serious imbalance—lagging economic development, lagging carbon emission and lagging economic development. In the past five years, the coordinated development degree of the two systems has increased year by year, and the benign mutual feedback mechanism between the two systems has gradually formed. However, regional economic development has lagged due to the impact of the COVID-19 epidemic, so speeding up regional economic development while protecting the environment is recommended.

Keywords: industrial park; carbon emission; economy; coupling

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1. Introduction

A large amount of human excreta and pollutants generated by the industrial sector are collectively sent to wastewater treatment plants for processing [1]. The resulting greenhouse gas emissions, including carbon dioxide, during the wastewater treatment process, account for approximately 2–5% of the total carbon emissions in society [2]. This has garnered significant attention from scholars both domestically and internationally [3–8]. Not only is China one of the largest greenhouse gas emitting countries globally, but it is also one of the fastest-growing economies [9,10]. China has over 2500 industrial parks at or above the provincial level, with the economic output of these industrial zones accounting for over 50% of the national total [11]. In 2020, China made a commitment to the world to achieve carbon peak before 2030, which puts additional pressure on the industrial economy to reduce carbon emissions during its rapid development [12]. Therefore, effectively balancing the economic development of industrial parks with green and low-carbon growth is one of the pressing issues that China urgently needs to address [13].

Wastewater treatment is an important aspect in preventing water pollution caused by industrial production, and scholars both domestically and internationally have conducted in-depth research on carbon emissions in the wastewater treatment process. Ma Xin (2011) compared and analyzed the carbon emissions of different treatment processes and scales in municipal wastewater plants using the calculation methods provided in the Intergovernmental Panel on Climate Change guidelines [14]. Yan Xu et al. (2018) analyzed the spatiotemporal distribution characteristics of greenhouse gases in urban wastewater plants in China [15]. In addition, Yu Jiao et al. (2020) conducted a study on carbon emissions from the wastewater treatment system in Zhengzhou city from the perspective of "water-energy-carbon" correlation [16]. Tian Peipei (2021) explored the coupled relationship between "water-energy-carbon" in China using a multi-regional input-output model (MRIO) [10]. Liu Yi (2019) discussed the coordinated development relationship between water environment quality and socio-economic factors in the Nansihu Basin in Shandong Province using the Environmental Kuznets Curve (EKC) model [17]. It can be observed that most scholars have conducted research on the carbon emissions in wastewater treatment processes, and some have analyzed the coordination between socio-economic development and water environment quality, while few have studied the coupled relationship between carbon emissions from wastewater treatment and regional economic development.

The Northwestern inland region possesses abundant coal resources, and while developing the coal chemical industry, the carbon emissions generated from wastewater treatment processes are also continuously increasing. With the implementation of the national dual-carbon policy, there exists a mutually dependent and restrictive relationship between regional carbon emissions and economic development. To accurately assess the level of coordination between regional carbon emissions and economic development and promote the coordinated development of water pollution control and the economy, this paper focuses on a key energy and chemical industrial park in the northern part of Shaanxi Province. Based on quarterly sewage water quality monitoring data and annual economic development statistics from 2016 to 2020, the paper uses the Intergovernmental Panel on Climate Change carbon emission calculation method [18] to analyze the dynamic evolutionary characteristics of carbon emissions from industrial wastewater treatment in the industrial park. By adopting the composite index method, the paper constructs the sewage treatment carbon emission index and economic development index, and for the first time proposes an economic development index for unit carbon emissions from wastewater treatment. Finally, this paper utilizes a coupling coordination degree model [19] to analyze and establish the coupling coordination relationship between carbon emissions from industrial wastewater treatment and regional economic development in the industrial park, aiming to evaluate the coordination between carbon emissions and economic development in the industrial park and provide reference for its low-carbon sustainable development.

2. Overview of the Study Area

The Shaanxi Northern Energy and Chemical Industrial Park is situated in the transitional area between the Loess Plateau and Inner Mongolia Plateau, at the intersection of the Mu Us Desert and the Ordos Basin. It experiences a continental monsoon climate characterized by significant temperature variations. The industrial zone boasts abundant coal resources, with a coal reserve of approximately 34 billion tons. The area has established a 1.15 million tons/year indirect coal liquefaction project, a 600,000 tons/year coal-to-olefins project, a 1.8 million tons/year coal-to-methanol project and a 10 million tons/year coal-to-electricity project, making it a pivotal national energy and chemical base. The industrial park is equipped with one wastewater treatment plant, with a processing capacity of 30,000 tons/day. The treatment process employs a "pre-treatment + membrane concentration + evaporation crystallization" technique, with all treated reclaimed water being reused, and the resulting salt mud being transported to a landfill. Figure 1 illustrates the process flow of the wastewater treatment plant in the park and the carbon emission diagram.

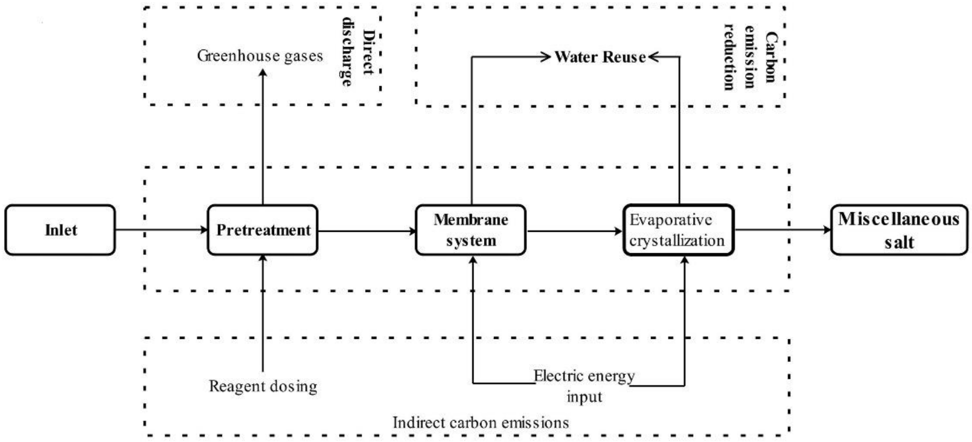

Figure 1. Schematic diagram of process flow and carbon emissions of the sewage treatment plant.

3. Research Method

3.1. Data Description

The temporal evolution of carbon emissions from wastewater treatment in the industrial park spans the years 2016 to 2020. The carbon emission indicators encompass class 3 direct carbon equivalent emissions, namely CO_2, CH_4 and N_2O. Additionally, class 4 indirect carbon emissions indicators are considered, including electricity consumption, lime usage, hydrochloric acid usage, PAM (polyacrylamide) usage and disinfectant usage (Hangzhou Shangtuo Environmental Technology Co., Ltd, Hangzhou, China). The carbon emission data used in this study are derived from the production statistics of the wastewater treatment plant for the years from 2016 to 2020. Economic development data are sourced from the statistical records of the park's administrative committee for the same time frame (2016–2020). The carbon emission and the economic development data are shown in Tables 1 and 2:

Table 1. Basic data of carbon emission from sewage treatment in the industrial zone.

Year	Quarter	BOD Emission Reduction/kg	TN Emission/kg	HCO^{3-} Emission/kg	Power Consumption $\times 10^4$ kw/h
2016	1	0.76	0.72	532.78	337.11
	2	0.86	0.95	459.79	324.11
	3	0.82	1.20	308.37	327.50
	4	0.83	1.03	413.55	353.12
2017	1	1.15	1.66	517.67	389.63
	2	0.88	2.73	506.06	394.19
	3	1.04	2.40	704.65	403.54
	4	1.16	2.74	658.44	469.37
2018	1	0.86	3.77	711.37	438.67
	2	1.00	2.81	617.29	478.96
	3	0.92	1.11	635.31	511.97
	4	1.17	1.61	646.66	647.91
2019	1	0.85	1.77	610.62	543.54
	2	0.82	2.16	501.69	473.80
	3	0.81	1.40	652.22	498.77
	4	0.97	1.74	571.86	602.52
2020	1	0.93	3.61	532.84	568.74
	2	0.89	1.56	502.24	558.96
	3	0.89	2.22	619.04	517.50
	4	0.78	1.11	458.58	596.74

Table 2. Statistics of economic development in the industrial zones (unit: 100 million yuan).

Year	Total Operating Income	Regional Production Total Value	Total Industrial Output Value	Total Fiscal Revenue	Local Finance Income	Fixed Assets Investment
2016	630	290	280	19.0	3.5	26
2017	730	340	430	27.0	4.0	50
2018	650	260	340	36.0	5.9	75
2019	760	314	370	49.2	14.3	160
2020	870	357	446	39.1	7.3	175

3.2. Accounting of Carbon Emission from Sewage Treatment

3.2.1. Calculation of Direct Carbon Emissions

Direct carbon emissions in the wastewater treatment process refer to the direct release of CO_2, CH_4 and N_2O into the atmosphere during the water treatment processes [20]. These emissions are primarily determined by multiplying the reduction in pollutants such as BOD, COD, total nitrogen and alkalinity between the influent and effluent of the wastewater treatment plant by their respective emission factors. The calculation formula is as follows [21]:

$$\begin{aligned} T_{Direct} &= Q(BOD_{ex} - BOD)E_{CH_4 \cdot BOD} \times \beta_{CH_4} \\ &+ Q(TN_{ex} - TN)E_{N_2O \cdot TN} \times \beta_{N_2O} + Q(JD_{ex} - JD)E_{CO_2 \cdot JD} \end{aligned} \tag{1}$$

where, T_{Direct} represents the direct carbon emission, with the unit as kgCO_2e; Q represents the sewage treatment water volume, with the unit t; BOD_{ex}, JD_{ex}, JD_{ex} and BOD, TN, JD represent the influent and effluent BOD, COD and the concentration of TN, respectively, with the unit kg/t; $E_{CH_4 \cdot BOD}$, $E_{N_2O \cdot TN}$, $E_{CO_2 \cdot TN}$ represent CH_4 and N_2O emission factors (0.086, 0.035 and 0.721, respectively) for COD, BOD, TN and HCO^3-, emissions [18] and conversion factors for CH_4 and N_2O emissions converted to carbon equivalent emissions, at 25 and 298, respectively [18].

3.2.2. Calculation of Indirect Carbon Emissions

Indirect carbon emissions are generated by electricity and reagents consumption during sewage treatment, which includes biochemical process aeration, water pump lifting, sludge pressure filtration, air compressor, heat pump, electrical equipment and the consumption of all kinds of reagents. The calculation formula is as follows [21]:

$$T_{Indirect} = M_{CO_2 \cdot E} \times EF_{CO_2 \cdot E} + \sum_{i=1}^{n} M_{CO_2 \cdot Yi} \times EF_{CO_2 \cdot Yi} \tag{2}$$

In the formula, $T_{Indirect}$ represents the emission of CO_2 in indirect carbon emissions, measured in the unit of KgCO_2e; $M_{CO_2 \cdot E}$ represents the electric energy consumption of the sewage treatment plant, and its unit is KW/h; $EF_{CO_2 \cdot E}$ represents the CO_2 emission factor of electric energy consumption (0.997), measured in Kg (CO_2)/KW/h; $EF_{CO_2 \cdot Yi}$ represents the CO_2 emission factor consumed by class i chemicals (1.74 for lime, 25 for PAM, 1.4 for bactericide, and 1.6 for hydrochloric acid); and $M_{CO_2 \cdot Yi}$ represents the consumption of class i agents (Kg) [18].

3.3. Coupling Model

3.3.1. Construction of Index System

In order to accurately assess the coupled and coordinated relationship between carbon emissions from wastewater treatment and economic development in the industrial park, a comprehensive evaluation framework is constructed, guided by principles of scientific rigor, systematicity, representativeness and hierarchy, building upon relevant studies [22,23]. The carbon emission assessment system integrates seven indicators encompassing both direct and indirect carbon emissions from the wastewater treatment plant in the industrial park.

These indicators include the direct emissions of CO_2, CH_4 and N_2O from various stages of the wastewater treatment process, as well as carbon emissions resulting from energy and chemical consumption such as electricity, lime, hydrochloric acid, PAM and disinfectants. This framework effectively captures the carbon emission profile of the industrial park's wastewater treatment activities.

Regarding economic development, the evaluation framework primarily incorporates six indicators sourced from the industrial park's statistical bureau. These indicators encompass operational revenue, regional gross domestic product (GDP), total industrial output value, overall fiscal revenue, local fiscal revenue and fixed asset investment. Together, these indicators reflect the changes in both the scale and efficiency of the industrial park's economic development, as depicted in Table 3.

Table 3. Evaluation index system of carbon emission from sewage treatment and economic development.

System Layer	Subsystem Layer	Indicator Layer	Weight of Coefficient of Variation
Socio-economic development	Economies of scale	X_1 Operating income/100 million yuan	0.1319
		X_2 Gross regional product/100 million yuan	0.1241
		X_3 Gross industrial output value/100 million yuan	0.1814
	Economic benefits	X_4 Total fiscal revenue/100 million yuan	0.3396
		X_5 Local fiscal revenue/100 million yuan	0.6224
		X_6 Fixed assets investment/100 million yuan	0.6844
Carbon emission from sewage treatment	Direct carbon emissions	Y_1 CO_2 emission/t	0.1520
		Y_2 CH_4 carbon emission equivalent/t	0.1414
		Y_3 N_2O carbon emission equivalent/t	0.3018
	Indirect carbon emissions	Y_4 Carbon emission of electric energy consumption/t	0.1993
		Y_5 Carbon emission of hydrochloric acid consumption/t	0.1862
		Y_6 Lime consumption and carbon emission/t	0.2844
		Y_7 Carbon emission of PAM consumption/t	0.1066
		Y_8 Carbon emission of fungicide consumption/t	0.3578

3.3.2. Sewage Treatment Carbon Emission and Economic Development Index

Before conducting the calculation of a comprehensive index, it is necessary to eliminate the influence of different data dimensions by applying a range standardization to the base data.

The calculation formula for standardizing positive indicators is as follows:

$$r_{ij} = \left(x_{ij} - \min\{x_j\}\right) / \left(\max\{x_j\} - \min\{x_j\}\right) \tag{3}$$

The calculation formula for standardizing negative indicators is as follows:

$$r_{ij} = \left(\max\{x_j\} - x_{ij}\right) / \left(\max\{x_j\} - \min\{x_j\}\right) \tag{4}$$

The carbon emission of sewage treatment and the economic development system of the industrial zone are both complex systems composed of multiple factors. In this paper, the variation coefficient method [21] is used to objectively reflect the relative importance of each index. The carbon emission index $f(x)$ and the economic development index $g(x)$ are obtained by multiplying the standardized value and weighted summation. x_i (i = 1, 2, 3...m) represents the standardized carbon emission index, x_j (j = 1, 2, 3...n) represents the standardized economic development index, w_i and w_j are the corresponding weights of x_i and x_j, respectively. $f(x)$ and $g(x)$ are obtained by the following formulas:

$$f(x) = \sum_{i=1}^{m} w_i x_i \; g(x) = \sum_{j=1}^{n} w_j x_j \tag{5}$$

3.3.3. Economic Development Index of Unit Sewage Treatment Carbon Emission

To further elucidate the relationship between carbon emissions from wastewater treatment and the economic development index, this paper calculates the Economic Development Index per unit of sewage treatment carbon emission (CE) by computing the ratio between the two indices. The CE is obtained by dividing the Economic Development Index by the Sewage Treatment Carbon Emission Index.

$$CE = \frac{g(x)}{f(x)} \tag{6}$$

The level of $CE > 1$ indicates a higher level of regional economic development and green low-carbon development. When $CE = 1$, it signifies a balance between regional economic development and carbon emissions from wastewater treatment. On the other hand, when $CE < 1$, it suggests a lower level of regional economic development and green low-carbon development.

3.3.4. Coupling Coordinated Degree

Coupling degree is a physical concept that refers to the phenomenon of mutual influence caused by multiple interactions between two or more systems. Due to the existence of similarities in the coupling relationships between systems, this paper applies the concept of coupling degree to the study of the interaction between carbon emissions from wastewater treatment and economic development in industrial areas, aiming to provide references for improving the status of carbon emissions in industrial areas and achieving sustainable economic development. The formula for calculating the coupling degree is:

$$C = \left\{(f(x)g(x))/(f(x)+g(x))^2\right\}^{1/2} \tag{7}$$

Because the coupling degree reflects the strength of interaction between the two parties [23], in order to further characterize the level of coordinated development between carbon emissions from wastewater treatment and economic development, a coupling coordination degree model is introduced:

$$T = \alpha f(x) + \beta g(x) \tag{8}$$

$$D[f(x), g(x)] = \sqrt{CT} \tag{9}$$

In this formula, $f(x)$ is the carbon emission index, $g(x)$ is the economic development index, and C, T and D represent the coupling degree, comprehensive harmony index and coupling coordination degree of carbon emission and economic development, respectively; α and β represent the contribution share of carbon emission and economic development, respectively [24]. Because the two systems of carbon emission and economic development are in the same position in this study, $\alpha = \beta = 0.5$ is determined here. See Table 4 for the classification of coupling coordination types of carbon emission and economic development in industrial zones.

Table 4. Classification of coupling coordination types of carbon emission from sewage treatment and economic development.

<table>
<tr><th colspan="2">Type</th><th colspan="2">Subtype</th><th>Subtype</th><th>Status</th></tr>
<tr><td rowspan="9">Coordination period</td><td rowspan="9">0.6 < D ≤ 1</td><td rowspan="3">High-level coordination</td><td rowspan="3">0.8 < D ≤ 1</td><td>$f(x) - g(x) > 0.1$</td><td>High-level coordination-lagging economic development</td></tr>
<tr><td>$g(x) - f(x) > 0.1$</td><td>Advanced Harmonization—Carbon Lagging</td></tr>
<tr><td>$0 \leq \mid f(x) - g(x) \mid \leq 0.1$</td><td>High-level coordination</td></tr>
<tr><td rowspan="3">Intermediate coordination</td><td rowspan="3">0.7 < D≤0.8</td><td>$f(x) - g(x) > 0.1$</td><td>Intermediate coordination-lagging economic development</td></tr>
<tr><td>$g(x) - f(x) > 0.1$</td><td>Intermediate coordination—Carbon Lagging</td></tr>
<tr><td>$0 \leq \mid f(x) - g(x) \mid \leq 0.1$</td><td>Intermediate coordination</td></tr>
<tr><td rowspan="3">Primary coordination</td><td rowspan="3">0.6 < D≤0.7</td><td>$f(x) - g(x) > 0.1$</td><td>Primary coordination-lagging economic development</td></tr>
<tr><td>$g(x) - f(x) > 0.1$</td><td>Primary Coordination—Carbon Lagging</td></tr>
<tr><td>$0 \leq \mid f(x) - g(x) \mid \leq 0.1$</td><td>Primary coordination</td></tr>
</table>

Table 4. *Cont.*

Type		Subtype		Subtype	Status
Transition period	0.4 < D ≤ 0.6	Barely coordinated	0.5 < D ≤ 0.6	$f(x) - g(x) > 0.1$	Reluctant coordination-economic development lags behind
				$g(x) - f(x) > 0.1$	Barely Coordinated—Carbon Lagging
				$0 \leq \lvert f(x) - g(x) \rvert \leq 0.1$	Barely coordinated
		On the verge of imbalance	0.4 < D≤0.5	$f(x) - g(x) > 0.1$	On the verge of imbalance-lagging economic development
				$g(x) - f(x) > 0.1$	On the Verge of imbalance– Carbon Lagging
				$0 \leq \lvert f(x) - g(x) \rvert \leq 0.1$	On the verge of imbalance
Uncoordinated period	0 <D ≤ 0.4	Mild imbalance	0.3 < D ≤ 0.4	$f(x) - g(x) > 0.1$	Mild imbalance-lagging economic development
				$g(x) - f(x) > 0.1$	Mild imbalance—Carbon Lagging
				$0 \leq \lvert f(x) - g(x) \rvert \leq 0.1$	Mild imbalance
		Moderate imbalance	0.2 < D≤0.3	$f(x) - g(x) > 0.1$	Moderate imbalance-lagging economic development
				$g(x) - f(x) > 0.1$	Moderate imbalance—Carbon Lagging
				$0 \leq \lvert f(x) - g(x) \rvert \leq 0.1$	Moderate imbalance
		Severe imbalance	0 <D ≤ 0.2	$f(x) - g(x) > 0.1$	Serious imbalance-economic development lags
				$g(x) - f(x) > 0.1$	Serious imbalance—carbon emissions lag
				$0 \leq \lvert f(x) - g(x) \rvert \leq 0.1$	Severe imbalance

4. Results and Analysis

4.1. Carbon Emission Analysis

4.1.1. Analysis of Direct Carbon Emission Indicators

Based on the monthly average BOD, TN and HCO^{3-} data of influent and effluent of the wastewater treatment plant in the park from 2016 to 2020 and the statistical data of annual pollutant reduction, the accounting results of direct carbon emission indicators from 2016 to 2020 can be obtained through the calculation of Formula (1), as shown in Figure 2.

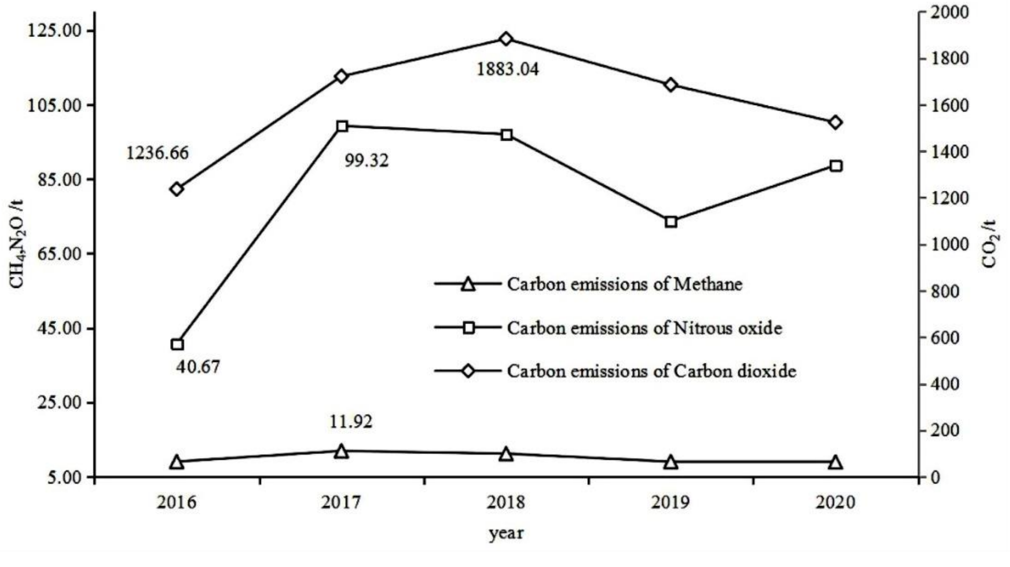

Figure 2. Annual change trend of direct carbon emission index in 2016–2020.

From the perspective of changes in key indicators such as CO_2, CH_4 and N_2O emissions at various stages of wastewater treatment, the primary contributor to direct carbon emissions is the CO_2 emission produced by the reaction between HCO^{3-} in wastewater and acid-neutralization. Following this, the carbon emission equivalent of N_2O plays a secondary role, while the carbon emission equivalent of CH_4 is minimal. In terms of annual variations, the carbon emission equivalents of CO_2, CH_4 and N_2O all exhibit an initial increase followed by a subsequent decrease trend. Among these, the peak emission of CO_2 occurred in 2018, reaching approximately 1883.04 metric tons. On the other hand, the peak emission of CH_4 and N_2O carbon equivalents both occurred in 2017, with values of 99.32 metric tons and 11.92 metric tons, respectively.

4.1.2. Coupling Coordinated Degree

Figure 3 illustrates the structural composition of carbon emissions from indirect sources, including electricity consumption and chemical reagent usage. It is evident from the graph that the primary contributor to indirect carbon emissions is the carbon emissions resulting from lime consumption, followed by electricity usage and hydrochloric acid consumption.

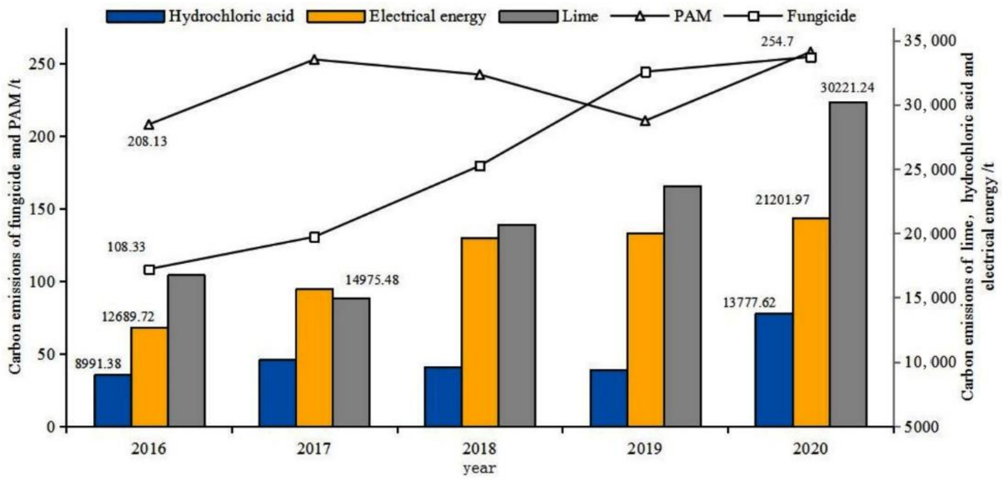

Figure 3. Annual change trend of indirect carbon emission index in 2016–2020.

Examining the annual variations in the indicators of indirect carbon emissions, a noticeable upward trend is observed in lime consumption, electricity usage, and disinfectant consumption. In contrast, the growth trends for PAM (polyacrylamide) and hydrochloric acid are relatively gradual. In the year 2020, carbon emissions from lime consumption, electricity usage and disinfectant consumption reached their peak values at 30,221.24 metric tons, 21,201.97 metric tons and 254.7 metric tons, respectively. These figures represent an increase of 80.32%, 67.08% and 135.11%, respectively, compared to the values in 2016. Notably, the most significant growth rate was observed in disinfectant consumption, followed by lime consumption. Furthermore, starting from 2018, the growth rate of carbon emissions generated by electricity consumption began to slow down, while the disparity between carbon emissions from lime and hydrochloric acid consumption became increasingly pronounced.

By considering both Figures 2 and 3, it can be deduced that the carbon emissions resulting from lime consumption exhibit an inverse relationship with CO_2 emissions. In other words, as the alkalinity represented by HCO^{3-} emissions from industrial enterprises within the park decreases, leading to reduced CO_2 emissions, the quantity of lime added to the wastewater treatment plant increases, consequently contributing to higher levels of indirect carbon emissions.

4.1.3. Analysis of Carbon Emission Results

The annual variations in direct carbon emissions and indirect carbon emissions from wastewater treatment are depicted in Figure 4. The contrasting yearly trends between direct and indirect carbon emissions are primarily influenced by fluctuations in the wastewater quality and quantity discharged by the industrial enterprises within the park. Direct carbon emissions exhibit a pattern of initial increase followed by a decrease, while indirect carbon emissions display a consistent upward trend. In the year 2020, the peak value of indirect carbon emissions was reached at 65,713.64 metric tons, approximately 1.7 times higher than the carbon emissions in 2016. The most substantial increase occurred between 2019 and 2020, primarily attributed to a significant rise in lime consumption.

From a general perspective, carbon emissions from industrial wastewater treatment have been steadily increasing year by year. Indirect emissions contribute significantly to overall carbon emissions, accounting for 97.6% of the total carbon emissions in 2020, while direct carbon emissions constitute only 2.4%. Considering Figure 3, it is evident that in 2020, the largest share of indirect carbon emissions is attributed to lime consumption, accounting for 46.0%, followed by electricity consumption (32.3%) and disinfectant usage contributing the smallest share at only 3.9%.

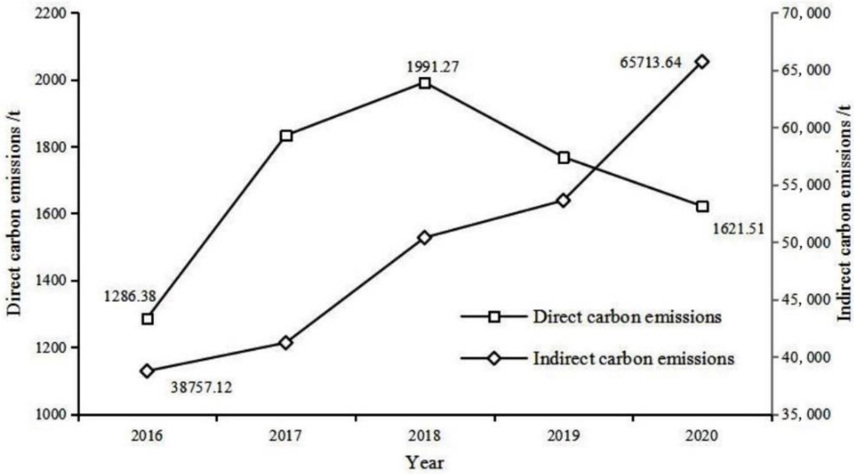

Figure 4. Annual change in direct and indirect carbon emissions from 2016 to 2020.

4.2. Coupling Coordination Analysis

4.2.1. System Index Analysis

The carbon emission index of industrial area water treatment, the economic development index and the economic development index per unit of carbon emission from water treatment can be calculated by Formulas (5) and (6), as shown in Figure 5. From 2016 to 2018, the Carbon Emission Index demonstrates a continuous upward trend. In the years 2019 to 2020, the index first experiences a decline followed by an increase, aligning closely with the annual variations observed in the major carbon emission indicators. This pattern reflects the comprehensive status of carbon emissions from industrial wastewater treatment.

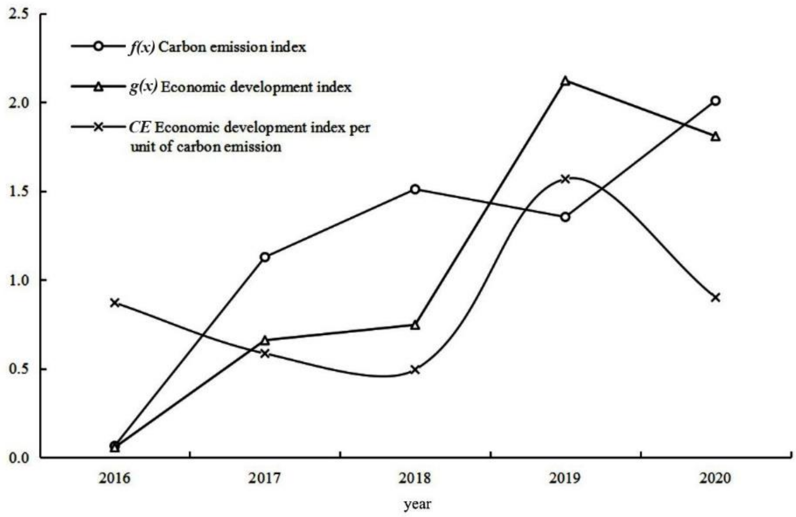

Figure 5. Annual changes of sewage treatment carbon emission index, economic development index, economic development index of carbon emission per unit of sewage treatment.

Within the economic development system, both economic efficiency and economic scale show rapid growth from 2016 to 2019. Notably, the growth rate in 2018 is relatively modest due to the impact of declining resource-based industries, such as coal. Additionally, the Economic Development Index experiences a decrease in 2020 compared to 2019, likely influenced by the disruption caused by the COVID-19 pandemic on the Chinese economy. This signifies a trend of an initially rising and then falling Economic Development Index.

Examining the Economic Development Index per unit of wastewater treatment carbon emissions, this index displays a trend of initial decline, followed by an increase, and then another decline. The lowest value for this index is observed in 2018 (0.49), while the highest value is recorded in 2019 (1.57).

Overall, both industrial wastewater treatment carbon emissions and the economic development index exhibit a consistent upward trend. In the early stages, the economic development index was lower than the carbon emission index. However, following a recovery in the coal industry in 2019, the economic development index surpassed the wastewater treatment carbon emission index. In 2020, the economic development index once again fell below the carbon emission index. This pattern indicates that the economic development of the industrial area has exerted a certain influence on wastewater treatment carbon emissions. It highlights the role of economic growth in promoting green and low-carbon development within the park, while favorable low-carbon and environmental conditions have also provided a foundation for the sustainable development of the regional industrial economy.

4.2.2. Change in Coupling Coordination Degree and Classification of Coupling Coordination Type

The coupling coordination degree between the sewage treatment carbon emission and the economic development system in the industrial area can be calculated by Formulas (8) and (9), as shown in Figure 6. The coupling coordination degree between the two systems shows an upward trend year by year. In 2016–2017, the carbon emission index and economic development index of sewage treatment in industrial zones showed a rapid growth trend, so the coupling coordination degree of the two systems increased the most; In 2017–2018, with the slowdown of the growth rate of carbon emissions and economic development index, the growth rate of the coupling coordination degree of the two also began to decrease; in 2018–2020, the economic development index first increased and then decreased, while the carbon emissions index first decreased and then increased, and the asynchrony between the two changes led to a further slowdown of the coupling coordination degree.

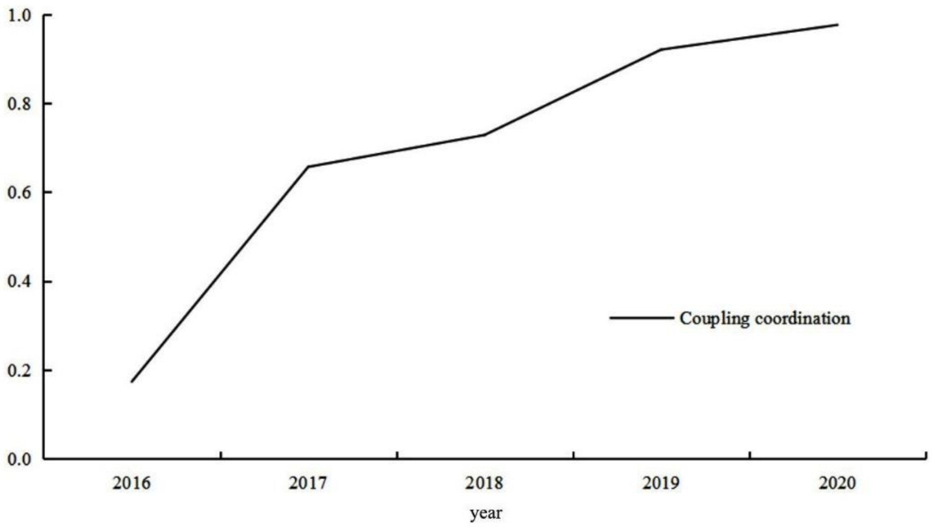

Figure 6. Coupled co scheduling of sewage treatment carbon emission and economic development.

According to Table 5, it is evident that in 2016, the coupling and coordination type between industrial wastewater treatment carbon emissions and economic development in the region was in a transitional phase, with a coupling coordination degree of 0.173, indicating a state of severe imbalance. From 2017 to 2018, the average coupling coordination degree for carbon emissions and economic development was 0.693, indicating a stage of primary and intermediate coordination within the coordination period. Economic development lagged behind carbon emission capacity during this time. In the years 2019 to 2020, the coupling and coordination type reached the advanced coordination stage within the coordination period, transitioning from a state of carbon emission lag to economic development lag.

Table 5. Types of coupling coordination degree between sewage treatment carbon emission and economic.

Year	Degree of Coordination	Type	
2016	0.173	Type incompatibility period	Severe imbalance
2017	0.657	Coordination period	Primary coordination-lagging economic development
2018	0.728	Coordination period	Primary coordination-lagging economic development
2019	0.920	Coordination period	Advanced coordination—Carbon Lagging
2020	0.976	Coordination period	High-level coordination—economic development lags

Overall, with the continuous changes in industrial wastewater treatment carbon emissions and regional economic development, the two systems remain in a dynamically coupled state. In 2016, the industrial area's economic development was just beginning, with enterprises starting production adjustments. Wastewater treatment carbon emissions were low, resulting in a lack of coordination between industrial carbon emissions and the economic system. From 2017 to 2018, although industrial carbon emissions were relatively low, the economic development level within the industrial area was even lower, leading to economic development lag. In 2019, industrial carbon emissions slowed down, with a decrease in the carbon emission index. However, the economic development index surged significantly due to the recovery of the coal economy, resulting in carbon emissions lagging economic development changes. In 2020, the impact of the COVID-19 pandemic led to a decline in industrial economic indicators. Paradoxically, carbon emission indicators began to rise noticeably, causing economic development to lag carbon emissions during this period.

5. Discussion

5.1. The Dynamic Evolutionary Characteristics of Industrial Wastewater Treatment Carbon Emissions

Combining Figures 2 and 4, it can be observed that the annual variations in direct carbon emissions from industrial wastewater treatment align with the trends in CO_2 emissions from the wastewater plant. In 2018, CO_2 emissions reached their peak (1883.04 metric tons), accounting for approximately 94.6% of the total direct carbon emissions that year. In contrast, the carbon emission equivalents of CH_4 and N_2O constituted only 5.4%. This pattern contrasts with the high proportion of organic carbon emissions in urban domestic wastewater treatment.

When considering Figures 3 and 4, the growth trend of indirect carbon emissions from industrial wastewater treatment corresponds to the trends in carbon emissions resulting from electricity consumption and lime consumption. The slower growth in indirect carbon emissions in 2019 compared to 2018 was mainly influenced by lower electricity consumption during that period. However, in 2020, there was a significant increase in indirect carbon emissions compared to 2019. This increase can be attributed to a decrease in the HCO^{3-} content in wastewater discharged by park enterprises, along with a substantial increase in the usage of lime and hydrochloric acid in the wastewater treatment plant.

Kyung et al. reported that chemical use is the major source of indirect carbon emissions, the proportion was 58.8% [25]. In this study, the use of chemical agents accounted for 65.3% of indirect carbon emissions in 2020.

5.2. Analysis on the Change in the Economic Development Index of Carbon Emission from Unit Sewage Treatment

As shown in Figure 5, the economic development index of carbon emission per unit of sewage treatment in 2016–2020 was 0.87, 0.58, 0.49, 1.57 and 0.90, of which the index shows a decreasing trend in 2016–2018, indicating that the economic and low-carbon development level of the industrial zone has been decreasing, which is mainly related to the low level of wastewater treatment at the early stage of the development of the park and the decline of the coal economy. In 2019, the index was greater than 1, which was mainly related to the reduction of carbon emissions from the sewage treatment in the park and the rebound of the coal economy. In 2020, the index was lower than in 2019, but higher than the value in 2016–2018, which was related to the economic downturn due to the New Crown Epidemic on the one hand, and the growth of carbon emissions from wastewater treatment due to stricter environmental requirements on the other.

5.3. Coupling Coordination Analysis of Sewage Treatment Carbon Emission and Social and Economic Development in Industrial Area

The coupling and coordination level between industrial wastewater treatment carbon emissions and regional economic development in the industrial area is generally high. Except for the year 2016, during which the carbon emission system and the economic development system were in a state of imbalance, the years 2017 to 2020 all fall within a coordinated period (with an average coupling coordination degree of 0.82), and both 2019 and 2020 reached an advanced coordination stage. The changes in the composite indices of the two systems reflect their continuous dynamic coupling state. In the early stages, when the carbon emission system and the economic system composite indices grow synchronously, the coupling coordination degree exhibits an upward trend. In the middle stage, as the carbon emission index starts to decline, the asynchronous changes in the two systems lead to a slowdown in the increase in the coupling coordination degree. In the later stage, as the carbon emission index begins to rise and the economic development index begins to decline, the increase in the coupling coordination degree further slows down.

From a temporal perspective, the coupling and coordination status of the two systems in the industrial area can be divided into four stages: severe imbalance (1 year)—economic development lag (2 years)—carbon emission lag (1 year)—economic development lag (1 year). This illustrates an evident influence of economic development changes on wastewater treatment carbon emissions in the industrial area, gradually forming a positive feedback mechanism between the two systems.

In addition, it is also necessary to continue to increase environmental protection investment through the recovery of biogas and biomass in the sewage and other effective measures to carry out carbon emission reduction in sewage treatment [24], and further promote the low-carbon sustainable development of the regional industrial economy.

6. Conclusions

This paper analyzes the trend of carbon emission of sewage treatment in industrial zone, discusses the coupling coordination and interaction between carbon emission of sewage treatment and economic development, and provides a theoretical basis for the coordinated development model of regional environment and economy.

(1). The carbon emissions from industrial wastewater treatment in the industrial area have shown a consistent upward trend in tandem with economic growth. Among these emissions, indirect carbon emissions were the primary contributors, accounting for 97.6% of the total carbon emissions in 2020, while direct carbon emissions constituted only 2.4%. Within the indirect carbon emissions in 2020, the largest contributor is carbon emissions from lime consumption, accounting for approximately 46.0%, followed by electricity consumption (32.3%). On the other hand, the primary contributors to direct carbon emissions are CO_2 emissions produced from the reaction of HCO^{3-} in industrial wastewater, followed by the carbon emission equivalents of N_2O.

(2). The coupling and coordination level between industrial wastewater treatment carbon emissions and the economic development system in the industrial area is generally high. This overall level falls within the advanced coordination stage in the past four years. This suggests that regional economic growth contributes to enhancing the green and low-carbon development level of the industrial park. Moreover, favorable environmental conditions provide a foundation for the sustainable development of regional economies. In the future, we should accelerate regional economic development and change the status quo of lagging economic development while strengthening environmental pollution control.

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Data Availability Statement: The carbon emission data used in this study are derived from production statistics of the wastewater treatment plant for the years 2016 to 2020. Economic development data are sourced from the statistical records of the park's administrative committee for the same time frame (2016–2020).

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References

1. Chen, W.H.; Yang, J.H.; Yuan, C.S.; Yang, Y.-H. Toward Better Understanding and Feasibility of Controlling Greenhouse Gas Emissions from Treatment of Industrial Wastewater with Activated Sludge. *Environ. Sci. Pollut. Res.* **2016**, *23*, 20449–20461. [CrossRef] [PubMed]
2. Senatore, V.; Zarra, T.; Pahunang, R.R.; Oliva, G.; Belgiorno, V.; Ballesteros, F.C., Jr.; Naddeo, V. Sustainable Odour and Greenhouse Gas Emissions Control in Wastewater Treatment Plant by Advanced Biotechnology Based System. *Chem. Eng. Trans.* **2021**, *85*, 25–30. [CrossRef]
3. Zhou, Z.; Zhuang, G.; Chen, Y. Evaluation of Low-Carbon City Construction: Theoretical Basis, Analytical Framework and Policy Implications. *Chn. Popu. Res. Envi.* **2018**, *28*, 160–169.
4. Zhai, M.; Shao, Y.; Xu, F.J. Countermeasures on greenhouse gas emission redution for the wastewater treatment plants of Xi'an. *Environ. Eng.* **2016**, *34*, 23–26.
5. Singh, P.; Kansal, A. Energy and GHG Accounting for Wastewater in Frastructure. *Resour. Conserv. Recy.* **2018**, *128*, 499–507. [CrossRef]
6. Singh, P.; Kansal, A.; Carliell-Marquet, C. Energy and Carbon Footprints of Sewage Treatment Methods. *J. Environ. Manag.* **2016**, *165*, 22–30. [CrossRef] [PubMed]
7. Xie, Q.J.; Han, P.F.; Chen, S.L.; Wang, L.; Zhen, M.X.; Du, C.J. The Characteristics of CO_2 Emissions in Sewage Treatment Plant with CAST Process. *Environ. Sci. Technol.* **2019**, *32*, 39–44.
8. Zawartka, P.; Burchart-Korol, D.; Blaut, A. Model of Carbon Footprint Assessment for the Life Cycle of the System of Wastewater Collection, Transport and Treatment. *Sci. Rep.* **2020**, *10*, 5799. [CrossRef] [PubMed]
9. Liu, X.; Dai, H.; Wada, Y.; Kahil, T.; Ni, J.; Chen, B.; Chen, Y.; Guo, C.; Pan, C.; Liu, X. Achieving Carbon Neutrality Enables China to Attain Its Industrial Water-Use Target. *One Earth* **2022**, *5*, 188–200. [CrossRef]
10. Tian, P.P. Water-Energy-Carbon Nexus in China's Trade Network: An Analysis with Multi-Regional Input-Output Paradigm. Ph.D. Thesis, North China Electric Power University, Beijing, China, 2021. [CrossRef]
11. Guo, Y.; Tian, J.; Chen, L. Managing Energy Infrastructure to Decarbonize Industrial Parks in China. *Nat. Commun.* **2020**, *11*, 981. [CrossRef] [PubMed]
12. Notice of the State Council on Issuing the Action Plan for Carbon Peak before 2030. Available online: http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm (accessed on 18 August 2023).
13. Zhu, E.Y. Study on the Spatialtemporal Pattern of Carbon Emission and Its Response to Urbanization in Zhejiang Province. Ph.D. Thesis, North China Electric Power University, Hangzhou, China, 2020. [CrossRef]
14. Ma, X. Greenhouse Gas Emission Analysis from Municipal Sewage Treatment Plants of China. Master's Thesis, Beijing Forestry University, Beijing, China, 2011.

15. Yan, X.; Qiu, D.Z.; Guo, D.L.; Qi, X.H.; Zheng, S.K.; Cheng, K.; Sun, J.H.; Liu, J.W. Emission Inventory of Greenhouse Gas from Urban Wastewater Treatment Plants and Its Temporal and Spatial Distribution in China. *Environ. Sci.* **2018**, *39*, 1256–1263.
16. Yu, J.; Zhao, R.Q.; Xiao, L.G.; Zhang, L.J.; Wang, S.; Chuai, X.W.; Han, Y.C.; Jiao, S.X. Emission Inventory of GreenhouseGas from Urban Wastewater TreatmentPlants and Its Temporal and Spatial Distribution in China. *Resour. Sci.* **2020**, *42*, 1052–1062.
17. Wang, D. Carbon Emissions, Economic Development and Environmental Protection Coupling in China. Master's Thesis, Northwest Normal University, Lanzhou, China, 2020. [CrossRef]
18. Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *IPCC Guidelines for National Greenhouse Gas Inventories, Cambridge*; Cambridge University Press: Cambridge, UK, 2006.
19. Rao, X.H.; Lin, X.Z.; Li, J.B.; Chen, Q.; Chen, W.H. Analysis of coupling coordination between social economy and water environment quality in river basin. *China Environ. Sci.* **2019**, *39*, 1784–1792.
20. Malila, R.; Lehtoranta, S.; Viskari, E.-L. The Role of Source Separation in Nutrient Recovery—Comparison of Alternative Wastewater Treatment Systems. *J. Clean. Prod.* **2019**, *219*, 350–358. [CrossRef]
21. Zhai, G.H.; Zuo, X.F. Spatial Differences and Influencing Factors of CarbonEmissions from Urban Wastewater Treatment in China. *J. Shijiazhuang Tiedao Univ.* **2020**, *14*, 1–10+24.
22. Zhang, S.S.; Zhang, L.C.; Li, G.; Li, C.F.; Wu, Z.X. Coordination analysis between water quality and economic development in Lake Qiandao basin. *J. Shijiazhuang Tiedao Univ.* **2014**, *26*, 948–954.
23. Liu, Y. Study on the Coordinated Development between Water Environmental Quality and Social Economy in Nansi Lake Catchment. Master's Thesis, Jinan University, Jinan, China, 2020. [CrossRef]
24. Almomani, F.; Al Ketife, A.; Judd, S.; Shurair, M.; Bhosale, R.R.; Znad, H.; Tawalbeh, M. Impact of CO_2 Concentration and Ambient Conditions on Microalgal Growth and Nutrient Removal from Wastewater by a Photobioreactor. *Sci. Total Environ.* **2019**, *662*, 662–671. [CrossRef] [PubMed]
25. Kyung, D.; Kim, M.; Chang, J.; Lee, W. Estimation of greenhouse gas emissions from a hybrid wastewater treatment plant. *J. Clean. Prod.* **2015**, *95*, 117–123. [CrossRef]