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Investigation of key technologies for energy saving and consumption reduction in chongqing municipal wastewater treatment plants based on carbon emission reduction contribution

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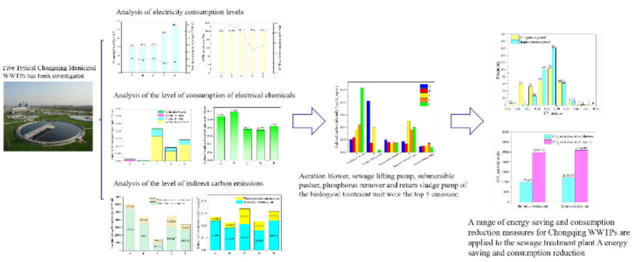
Graphical abstract



Abstract

In this paper, based on the factors of treatment process, treatment scale, as well as water quality, the level and distribution of electricity consumption, drug consumption, and indirect carbon emission of five typical wastewater treatment plants (WWTPs) were examined. The distribution of electricity consumption within the WWTPs were analyzed in terms of wastewater treatment units. The results uncovered that the biological treatment unit was the treatment unit with a high percentage of electricity consumption in the WWTPs. Carbon emissions of main units in the WWTPs presented that the aeration blower, sewage lifting pump, submersible pusher, phosphorus remover and return sludge pump of the biological treatment unit were the top 5 emission units of carbon emissions in the WWTPs, and the key influencing factors of the carbon emissions of the main carbon emission units had been analyzed. Combined with the current situation of sewage treatment energy consumption in Chongqing, the analysis put forward a library of energy saving and consumption reduction measures for Chongqing WWTPs, which applied them to the sewage treatment plant A energy saving and consumption reduction renovation project.

Keyword: Carbon emission, WWTPs, power consumption, energy conservation and emission reduction

1. Introduction

Carbon neutrality means that the total amount of carbon dioxide (CO_2) emissions produced directly or indirectly by an enterprise, group or individual within a certain period of time can be fully offset through tree planting, energy conservation and emission reduction, thus realizing zero carbon dioxide emissions (Z. Liu *et al.,* Zhang *et al.,* Bai *et al.*). The importance of water systems is increasingly being highlighted in the context of climate change and rapid urbanization(Wei *et al.*). From an indispensable basic resource to a vital environmental carrier, the demand for water has risen while the water environment has been affected to varying degrees, leading to further energy consumption(Chen and Lin, Liang *et al.*). In the management of the urban water system, if focusing on the conflict between water supply and demand, rainwater management, and water environment management rather than pay attention to the carbon emissions generated by the urban water system in the operation and maintenance process, it will lead to unsustainable and unfavorable social development(J. Li *et al.,* X. Liu *et al.*; Zhao *et al.*). Cities may pay more attention to green development, in the process of planning and management of urban water system, increasing energy saving and carbon emission reduction targets, in order to better cope with the pressure of carbon emission reduction and provide a continuous power for the green development of the city (Cheng *et al.*; Sun *et al.*).

As an important public utility, municipal wastewater treatment systems act as a carbon source, using large amounts of electricity to indirectly cause large amounts of carbon emissions in the process of treating water quality and combating pollution (Woon *et al.*). Sewage treatment is a high energy consumption industry and meanwhile an important carbon emission industry, because energy consumption (fossil fuels) will produce greenhouse gases CO_2 (S. Li *et al.*). It is estimated that if conventional wastewater treatment methods are used, for every 1 m^3 of municipal wastewater treated, 6.5 MJ of energy, equivalent to 0.22 kg of standard coal, will be wasted and 0.62 kg of CO_2 will be generated at the same time (Panepinto *et al.*). In 2021, the total amount of wastewater discharged in China will be 108.51 billion tons, and if conventional wastewater treatment methods are used, about 7078 MJ of energy may be wasted, which is equivalent to 24.29 million tons of standard coal, about 66.42 million tons of CO_2 will be discharged into the environment. Therefore, in order to realize sustainable development, it is necessary to study and plan a new sustainable social water cycle system from the perspective of reducing carbon emissions and energy consumption, protecting the natural environment and realizing the goal of sustainable development.

Greenhouse gas (GHG) emissions from municipal wastewater systems are beginning to be taken seriously(Willis *et al.*). It is estimated that non-CO_2 GHG emissions (N_2O and CH_4) from WWTPs are equivalent to about 4.6-5.2% of total global non-CO_2 GHG emissions from 2005 to 2030. The Intergovernmental Panel on Climate Change (IPCC) has shown that the greenhouse effect of N_2O and CH_4 is 265 times higher than that of CO_2, and therefore deserves special attention (Demir and Yapıcıoğlu; Fan *et al.*). WWTPs are characterized by high energy consumption, and wastewater treatment requires the consumption of large amounts of energy, reagents and other resources. In conventional WWTPs, about 25~40% of the operating costs are attributed to energy consumption (Gu *et al.*). There is no doubt that in view of environmental and economic sustainability, high energy consumption and low energy recovery efficiency will have a significant impact on the entire global wastewater industry. Currently, energy efficiency optimization of WWTPs are quite a hot topic in the scientific community (Kong *et al.*). Lowering wastewater treatment energy consumption is an important goal for carbon reduction in wastewater treatment systems(Singh and Kansal). In order to reduce the operating cost and energy consumption, and torealize carbon neutral, many governments and scholars have investigated the possibility of obtaining energy from wastewater and sludge by dissecting the pathways of energy use and energy recovery of wastewater treatment systems, based on the influencing factors of energy use of wastewater treatment systems and exploring the possibility of constructing a wastewater treatment system that is self-sustainable in terms of energy and the environmental benefits it brings (Bani Shahabadi *et al.*; Shen *et al.*; Du *et al.*).

At present, most of the studies on carbon emission assessment and accounting of domestic sewage treatment system are still focused on the macro-medium level such as the country and the city, while there are huge differences in the process and regional characteristics, resulting in huge differences in the carbon emission level of different studies, which may be unfavorable to the subsequent research on greenhouse gas emission reduction technologies and the development of related support policies. For WWTPs in Chongqing, the investigations of carbon emissions and carbon reduction potential are still a blank. Therefore, it is necessary to propose a carbon reduction strategy suitable for wastewater treatment system in view of the characteristics of Chongqing region. In this paper, the main research objectives include (1) selecting typical WWTPs in Chongqing to analyze the operational energy consumption as well as the indirect carbon emissions, and (2) selecting one of the typical WWTPs to conduct a study on energy saving and consumption reduction measures.

2. Research methods

2.1. Selection of research subjects

As of the end of 2021, there were 73 urban domestic WWTPs in Chongqing with a design scale larger than 10,000 m^3/d, with a total design scale of 4,610,000 m^3/d. After analyzing the literature research, the factors affecting the energy consumption of the operation of WWTPs mainly included the design scale of WWTPs, the treatment process, and the form of construction (Al-Anbari *et al.*; Vieira *et al.*; Barillon *et al.*; Fenu *et al.*). Therefore, this study on the urban domestic WWTPs of Chongqing was to select the research object after statistically analyzing the above aspects to ensure the representativeness of the research object. The five typical WWTPs were selected on the basis of Text S1.(At the end of the manuscript)

After analyzing the design scale, treatment process, construction form and other factors of the current sewage treatment plant in Chongqing, the following five sewage treatment plants were selected as typical sewage treatment plants in Chongqing to carry out this study.(Table S1, at the end of the manuscript)

2.2. Selection of indicators to characterize the level of energy consumption

At present, urban WWTPs were mainly to unit water volume power consumption (kW·h/m^3), unit pollutant reduction power consumption (kW·h/kgCOD or kW·h/kgNH_3-N) and unit water volume consumption (kg/m^3) as the energy consumption indicators. The energy consumption of WWTPs was closely related to the pollutants it removed, and the pollutants in the actual wastewater were of various types and contents. It was difficult to comprehensively analyze the actual wastewater power consumption by using the unit chemical oxygen demand (COD) reduction power consumption or unit NH_3-N reduction power consumption index. So it was necessary to introduce the total pollution power consumption index for comprehensive evaluation. This study proposed the calculation method of oxygen-consuming total pollutant (OCTP)(Silva *et al.*; Q. Chen *et al.*; J. Chen *et al.*; Xia *et al.*). Since the main pollutants in urban WWTPs were organic matter, nitrogen and phosphorus, and the oxygen consumption of pollutants was mainly generated by the decomposition of organic matter and ammonia nitrogen, only the role of organic matter and ammonia nitrogen were considered in the calculation of OCTP. For organic matter, its removal in the WWTPs can be considered as biological oxidative decomposition, then the biological oxygen demand (BOD) of wastewater can be used to represent the oxygen consumption of organic pollutants in wastewater in the wastewater treatment process. For ammonia nitrogen, whose oxygen consumption was contributed by nitrification, the biochemical reaction equation (1) was as follows:

$$NH_4^+ + 2O_2 \xrightarrow{nitrification\ bacteria} NO_3^- + H_2O + 2H^+ \quad (1)$$

According to the above equation, it can be obtained that the oxygen consumption of 1 g of ammonia nitrogen was 4.57 g of O_2. Then, the equation (2) for the total pollutant of oxygen consumption in the process of municipal wastewater treatment was:

$$OCTP=BOD+4.57NH_3\text{-}N \quad (2)$$

Where, BOD was the concentration of biological oxygen demand (BOD) of sewage, mg/L; NH_3-N was the concentration of ammonia nitrogen in sewage, mg/L.

In summary, this study used electricity consumption per unit of water (kW·h /m^3), OCTP and pharmaceutical consumption per unit of water (kg/m^3) to characterize the energy consumption level of the WWTPs.

2.3. Methodology for calculating indirect carbon emissions

Indirect emissions from the wastewater treatment system mainly came from the electrical energy consumption of the sewage lifting unit, aeration unit, material flow circulation unit, sludge treatment and disposal unit and the mechanical equipment in its treatment process, as well as the pharmaceuticals consumed in the operation of the treatment process unit, which mainly included lime used for the adjustment of the pH of the wastewater, carbon source used for the replenishment of COD, liquid chlorine used for subsequent disinfection of the wastewater, and flocculant and coagulant added in the thickening and dewatering process of the sludge. Each of these chemicals involved greenhouse gas emissions during their production and transportation.

Therefore, the formula for calculating the indirect carbon emissions from the sewage treatment plant was as follows:

2.3.1. Indirect emissions from electricity consumption

Indirect carbon emissions from the operation and maintenance of wastewater treatment structures due to electricity consumption were calculated with reference to the general provisions in the following formula (3-4):

$$\text{Total carbon emissions} = Ed \times EFd \quad (3)$$

$$CESd=(Ed \times EFd)/Q \quad (4)$$

Where, CES_d was carbon intensity of purchased electricity consumed for operation and maintenance, kgCO$_2$-eq/m^3; E_d represented total electricity consumption for operation and maintenance during the evaluation year, kWh/a; EF_d meant electricity emission factor for the area, kgCO$_2$-eq/kWh; Q was volume of water treated in the WWTPs, m^3, in terms of the volume of water meeting the standard quality.

Selection of emission factors: the scenarios and control purposes were different and divided into two main categories. The first category was to calculate greenhouse gas (GHG) emissions, using the annual average grid emission factor: the grid emission factor in 2021 was 0.5810 kg CO_2/kWh. The second category was to calculate GHG emission reductions, using regional grid baseline emission factors: Chongqing belonged to the Central China regional grid, and the emission factor was 0.8587 kg CO_2/kWh.

2.3.2. Indirect emissions from pharmaceutical consumption

Indirect carbon emissions from the operation and maintenance of wastewater treatment structures due to the consumption of pharmaceuticals calculated with reference to the general provisions in the following formula:

$$CES_{Cl} = \sum_{i=1}^{n}\left(M_{cl,i} \times EF_{cl,i}\right)/Q \quad (5)$$

Where CES_{cl} was indirect carbon emission intensity from the pharmaceuticals and materials, consumed in the sewage treatment process, kgCO$_2$-eq/m^3; $M_{cl,i}$ was total consumption of the i-th pharmaceutical agent in the evaluation year, kg/a; $EF_{cl,i}$-emission factor of the i-th agent, kgCO$_2$-eq/kg (Table S2); n was total use of n agents; Q was the volume of water treated in the WWTPs, m^3, the WWTPs to meet the standard water quality water.

3. Results and discussion

3.1. Analysis of the composition of energy consumption

The energy consumption of WWTPs were mainly divided into direct energy consumption and indirect energy consumption. Direct energy consumption was defined as the energy directly consumed by the on-site process in the wastewater treatment process, which was mainly electrical energy. Indirect energy consumption referred to the pharmaceutical materials required in the wastewater treatment process. Specifically, the operational energy consumption of the typical WWTPs in Chongqing included both electricity consumption and pharmaceutical consumption. Electricity consumption represented the electrical energy consumption of individual equipment, and pharmaceutical consumption mainly consisted of the consumption of pharmaceuticals such as carbon source for additional dosing, phosphorus remover for auxiliary phosphorus removal, disinfectant for disinfection, and polyacrylamide for sludge dewatering.

3.1.1. Analysis of electricity consumption levels

The annual power consumption of the five WWTPs selected in this study ranged from 1,637,200 to 9,307,700,000 kW·h, and the order of annual power consumption was A>B>D>E>C, which was in the same order of the volume of wastewater handled by the respective WWTPs, indicating that the annual power consumption of the WWTPs were mainly influenced by the annual volume of wastewater treated by the WWTPs. The annual electricity consumption of the WWTPs were greatly affected by the annual volume of sewage treated at the WWTPs.

As can be seen in Figure 1(a), the annual average power consumption per unit of wastewater of the 5 WWTPs ranged from 0.275-0.414 kW·h/m^3. The order of the annual average power consumption per unit of wastewater was: E>A>C>B>D. From Figure 1(b), the annual average power consumption per unit of OCTP reduction of the 5 WWTPs ranged from 0.920-1.944 kW·h/kg. The annual average OCTP reduction power consumption of the five WWTPs were ranked as A>B>C>E>D.

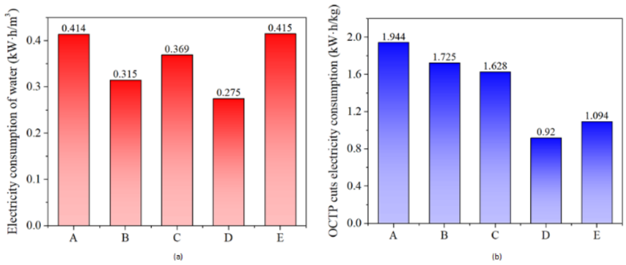


Figure 1. (a) Average annual electricity consumption per unit of water for 5 sewage plants; (b) annual average unit OCTP reduction power consumption for 5 WWTPs.

From the characterization of electricity consumption per unit of sewage power consumption and unit OCTP reduction power consumption two indicators, plant D in the five sewage treatment plants in the electricity unit consumption were low sewage treatment plant. Its annual average unit of sewage power consumption and the annual average unit of OCTP reduction of power consumption were 23% and 37% lower than the average of the five WWTPs, due to gravity-flow water intake, the operating load (88.5%) and the high concentration of pollutants in the influent (BOD5=219.53mg/L). The plant A had a high electricity unit consumption among the five WWTPs, and its annual average unit wastewater consumption and annual average unit OCTP reduction consumption were 16% and 33% higher than the average value of the five WWTPs, respectively. Because compared with other WWTPs, the electricity consumption of plant A also included the power consumption of the off-site lifting pumping station, as well as low influent concentration in 2021 (BOD5=138.58mg/L) and low operating load (61.6%), which was a large deviation from the design conditions and also a cause of the high electricity unit consumption.

From Figure 2(a), there was a correlation between the electricity consumption per unit of wastewater in the WWTPs and the operating load. The annual average electricity consumption per unit of wastewater of WWTPs A, B, C were at a high level among the study subjects, which may be due to the low operating loads of all the WWTPs. Taking WWTP A as an example, the operating load in 2021 was only 61.6%, which did not meet the design daily water treatment capacity of 100,000 t, and only 75% of the biological treatment unit was activated for daily operation, but the equipment design was matched by 100,000 t/d. In the case of insufficient load, there was little room for adjusting the parameters of high-power equipment such as lifting pumps and blowers that were matched with the designed water volume and the energy consumption was high. This may cause the overall electricity consumption to be on the high side. Since this study targeted five typical WWTPs, and the sample size was small. In general, the electricity consumption per unit of wastewater in WWTPs showed a tendency of decreasing with the increase of the operating load rate(Gurung *et al.*).

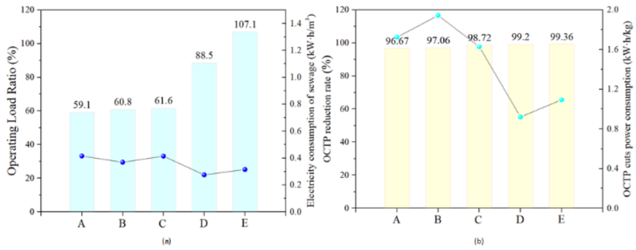


Figure 2. (a) Relationship between electricity consumption per unit of effluent and operating load in WWTPs; (b) relationship between electricity consumption per unit of OCTP reduction and OCTP reduction rate in WWTPs.

As can be seen in Figure 2(b), the power consumption per unit of OCTP reduction in WWTPs were closely related to the pollutants reduced by treatment. According to the OCTP formula, the OCTP reduction rate of the five WWTPs were calculated from the data of BOD and ammonia concentration in the influent and effluent of each WWTP. Overall, the power consumption per unit of OCTP reduction of plant A, B and C with lower OCTP reduction rate was significantly higher than that of plant D and E with higher OCTP reduction rate, which uncovered that under the premise of similar effluent standards, higher OCTP reduction rates revealed higher influent concentrations, and higher influent concentrations corresponded to lower OCTP reduction rates per unit of influent. However, since the sample size of this study was insufficient for five typical WWTPs, in general, the power consumption per unit of OCTP reduction in WWTPs tended to decrease with the increase of OCTP reduction rate(Wang *et al.*; Vaccari *et al.*).

3.1.2. Analysis of drug consumption levels

The primary types of pharmaceuticals used in WWTPs included carbon sources, phosphorus removers, disinfectants, and sludge flocculants. At this stage, more than 90% of urban sewage treatment plants in China adopted biological treatment process. In order to meet the high emission standards, most of the new plants and upgrading plants of the secondary treatment section selected A2O, oxidation ditch, sequencing batch reactor (SBR) and other denitrification and phosphorus removal processes. Some plants of the depth of the treatment section also increased the denitrification tank to ensure that the total nitrogen removal effect. Based on the need to provide enough electron donors for bacteria, denitrification process required a certain amount of easily degradable organic matter as an additional carbon source. When the carbon source in the influent water was insufficient, most of the WWTPs would choose to add carbon sources in different locations to improve the ability to remove nitrogen and phosphorus.

WWTPs B, C and D had additional carbon sources, and the amount of carbon sources to be added in 2021 will be 492.88 tons, 197.85 tons, and 255.72 tons, respectively. WWTP A and E did not have additional carbon sources, of which WWTP E was mainly due to its service scope for the commercial and residential areas in the central urban area of Yubei, which were mature and dense old communities. About 70% of the drainage sources were not equipped with septic tanks, and the water collected was basically urban domestic wastewater, with high concentration of pollutants in influent and high content of organic matter, so there was no need to add additional carbon sources.

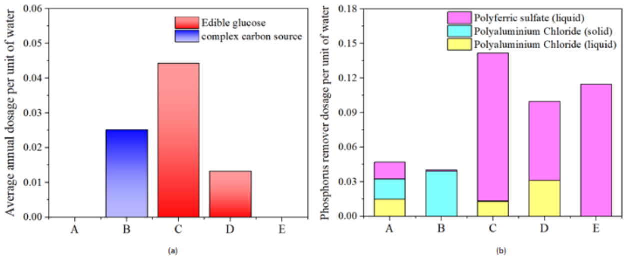


Figure 3. (a) Annual average unit water dosage for different carbon source types in 5 WWTPs; (b) phosphorus remover dosage per unit of water for 5 WWTPs.

Similarly, WWTP A was currently more than 90% of domestic sewage in the influent. While in the early stages of design, taking into full account the common problem of insufficient carbon sources affecting the effect of denitrification in Chongqing municipal WWTPs, only two small pre-settlement tanks were set up, and at the same time in the actual operation of the process of the primary sedimentation tank was not used (except for the case of incoming cement slurry water and grease). The purposes were to appropriately reduce the residence time and surface load of the primary sedimentation tank, as well as the primary sedimentation tank on the consumption of carbon in the sewage. From Figure 3(a), WWTP C, which also used a composite carbon source, possessed a higher average annual carbon input per unit of water (0.045 kg/m^3) than WWTP D (0.013 kg/m^3), which may be attributed from obvious scale effect, lower operating load and different types of process (C: oxidation ditch; D: A2O).

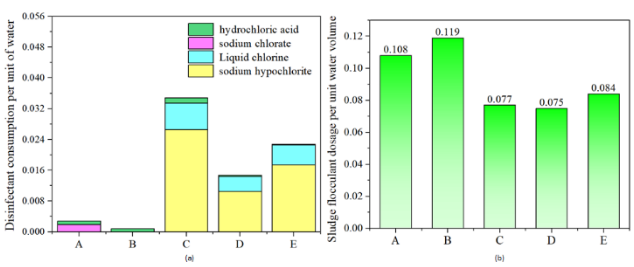


Figure 4. (a) Unit water consumption of disinfectants in 5 sewage treatment plants; (b) sludge flocculant dosage per unit of water for 5 sewage treatment plants.

All five WWTPs were dosed with phosphorus removers, and the average annual dosage of phosphorus removers per unit of water ranged from 0.040 to 0.142 kg/m^3 (Figure 3(b)). There were differences in the types of phosphorus removal agents selected by different sewage treatment plants. WWTP A mainly used phosphorus remover for poly iron (liquid), poly aluminum (solid) as well as poly aluminum (liquid) and the use of the three accounted for more than the average, respectively, 31.46%, 37.30%, 31.24%. WWTP B mainly used phosphorus remover for poly aluminum (solid), the use of 97.22%. WWTP C of the main phosphorus removal agents used polyaluminum (liquid) was mainly used, 90.42%. WWTP D mainly used polyferric (liquid) and polyaluminum (liquid), 31.35% and 68.65%. Phosphorus remover of WWTP E mainly adopted polyaluminum (liquid).

In order to kill or inhibit pathogenic microorganisms and harmful substances in wastewater, disinfectants were dosed at WWTPs to ensure that the treated water quality met discharge standards and environmental requirements. Disinfectants were added to all five WWTPs in this study. Among them, the disinfection method used in the WWTP B was UV disinfection as the main method, supplemented by chemical disinfection, while the rest of the WWTPs adopted chemical disinfection as the main method. From Figure 4(a), the range of annual average disinfectant raw material consumption per unit of water for the five WWTPs was 0.001-0.035 kg/m^3. Currently, the main method of sewage disinfection was to inject disinfectant into the sewage, and the commonly used disinfectants were liquid chlorine, ozone, sodium hypochlorite and ultraviolet light. Among the five WWTPs, the main disinfectant used in WWTP A was mainly liquid chlorine, supplemented by sodium hypochlorite, and the use of liquid chlorine accounts for 67.59% of the total amount of disinfectant. However, liquid chlorine was shifting to sodium hypochlorite-based dosing mode due to safety hazards. WWTPs C, D and E mainly adopted hydrochloric acid and sodium chlorate as raw materials for on-site preparation of chlorine dioxide, with hydrochloric acid usage accounting for 76.57%, 71.66% and 76.09% respectively. Storage of chemical disinfection reagents for underground WWTPs has demanding firefighting requirements, so the WWTP B operated with UV disinfection as the main disinfection mode and sodium hypochlorite disinfection as the supplementary disinfection mode.

For the purpose of meeting the requirement of dewatering sludge with water content less than 80% in urban WWTPs, sludge generally needed to be dosed and conditioned to improve its dewatering performance before dewatering treatment. As can be seen in Figure 4(b), the five WWTPs in this study were dosed with sludge flocculant polyacrylamide, and the average annual flocculant dosage per unit of sludge ranged from 0.075 to 0.119 kg/t. The amount of flocculant dosage was closely related to the sludge dewatering method. The amount of flocculant dosage per unit of sludge in WWTP B, which employed centrifugal dewatering process (0.119 kg/t), was slightly higher than that of other WWTPs adopting belt-type filter press dewatering (0.075-0.108 kg/t), mainly because centrifugal dewatering machine separated the mud and water through centrifugal action. The effect of flocculation of the sludge was more demanding, and thus the amount of flocculant used was also higher.

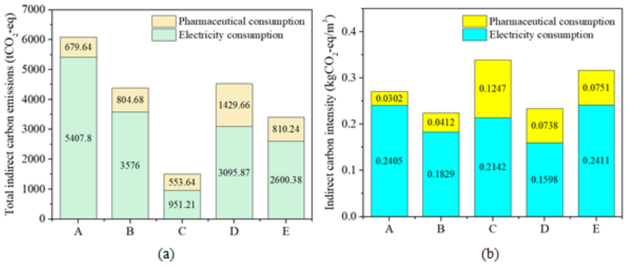


Figure 5. (a) Total indirect carbon emissions from 5 WWTPs in 2021; (b) indirect carbon emission intensity of 5 WWTPs in 2021.

3.2. Analysis of indirect carbon emission levels

From Figure 5(a), the total annual indirect carbon emissions of the five WWTPs selected in this study range from 1504.85~6087.44 tCO_2-eq, of which the total indirect emissions from electrical energy consumption account for the major part ranged from 951.21~5407.80 tCO_2-eq, and the total indirect emissions from pharmaceutical consumption comprised a series of from 553.64~1429.66 tCO_2-eq. The order of total annual indirect carbon emissions was A>D>B>E>C, which had a strong correlation with the size of sewage volume handled by each WWTP in 2021, with a linear correlation coefficient of 0.96, revealing that the total annual indirect carbon emissions of the WWTPs were mainly affected by sthe annual volume of sewage volume handled by the WWTPs. The correlation uncovered that the total annual indirect carbon emissions of the sewage treatment plants were mainly affected by the annual sewage treatment plant volume.

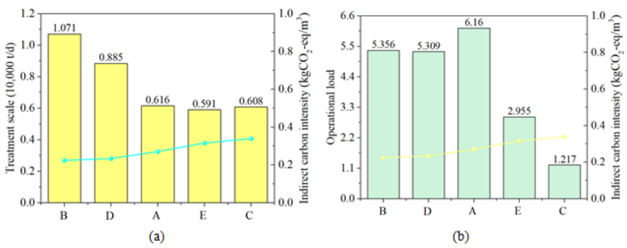


Figure 6. (a) Indirect carbon intensity versus operating load; (b) relationship between indirect carbon intensity and scale of treatment.

The annual average indirect carbon emission intensity of the five sewage treatment plants ranged from 0.224 to 0.339 $kgCO_2$-eq/m3, of which the carbon emission intensity of electric energy consumption ranged from 0.160 to 0.241 $kgCO_2$-eq/m^3, and that of pharmaceutical consumption spanned from 0.030 to 0.125 $kgCO_2$-eq/m^3 (Figure 5(b)). The order of magnitude of the average annual indirect carbon emission intensity was C>E>A>D>B. As can be seen in Figure 6(a), there was a good correlation between the indirect carbon emission intensity of the WWTPs and the operating load, with a linear correlation coefficient of 0.86. In general, the indirect carbon emission intensity of the WWTPs represented a decreasing trend with the increase of the operating load rate, owing to that the closer the operating load was to the 100% of the design condition. The operating power of the equipment in the plant was closer to the rated power of the selected equipment, and the equipment operated more efficiently, which in turn reduced the unit power consumption and indirect carbon emissions.

At the same time, a good correlation occurred between the indirect carbon emission intensity of sewage treatment plants and the treatment scale, with a linear correlation coefficient of 0.86. Overall, the indirect carbon emission intensity of sewage treatment plants was inclined to decrease with the increase of the treatment scale, which was mainly because large-scale sewage treatment plants presented an obvious scale effect.

In terms of the composition of indirect carbon emissions from sewage treatment plants, carbon emissions caused by electrical energy consumption were the most important source of indirect carbon emissions from sewage treatment plants, with the emission intensity accounting for 63.21%~88.84% of the total intensity of indirect emissions, and the carbon emissions caused by pharmaceutical consumption accounting for 11.16%~36.79% (Figure 7(a)). Further correlation analysis between carbon emission intensity and unit sewage power consumption exhibited that the unit sewage power consumption of the five WWTPs was 0.275~0.415 kW·h/m^3, and the correlation between carbon emission intensity and unit sewage power consumption was 0.68, leading to the indirect carbon emissions from WWTPs were greatly influenced by power consumption.

In Figure 7(b), the top five indirect carbon emission units in each of the five WWTPs had been investigated for emission intensity. The indirect carbon emission intensity in the five WWTPs were mainly concentrated in the aeration blower, sewage lifting pump, submersible pusher, phosphorus remover and return sludge pump in the biological treatment unit. The sum of its indirect carbon emission intensity accounted for 53.55%~83.39% of the total electricity consumption per unit of sewage in the plant. It could be seen that the use of phosphate remover and other chemicals may cause large carbon emissions. Therefore, carbon emission reduction in WWTPs cannot be limited to the electricity consumption unit, and meanwhile pay attention to the carbon emissions generated by the consumption of various types of pharmaceuticals.

3.3. Study on Energy Saving and Consumption Reduction Measures for a Typical WWTP

By fully analyzing the operation of the working conditions, the current situation of energy consumption and the problems, the WWTP A was investigated as an application case of energy saving and consumption reduction measures. The current operating load of WWTP A did not meet the design daily treatment volume of 100,000 m^3, and only 75% of the biological treatment unit was enabled for daily operation, with an average daily treatment volume of less than 50,000 m^3/day. In the case of insufficient load, for the design of water to match the high-power equipment parameters such as lifting pumps and blowers, there was a small space for adjustment and high energy consumption. In order to meet the operational requirements of water quality discharge standards, in the absence of conventional online instrumentation guidance in the biological pool, the main process of biological pool operation had been taken to experience the operation of the main intermittent aeration operation mode in order to avoid excessive aeration.

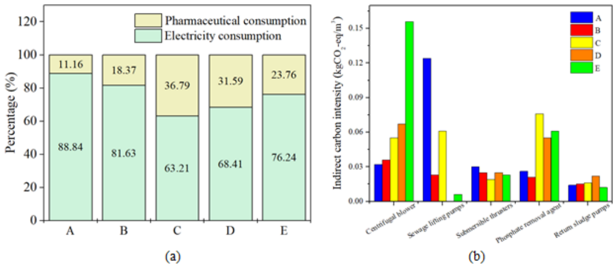


Figure 7. (a) Indirect carbon emission intensity electricity and pharmaceutical consumption share of 5 WWTPs in 2021; (b) carbon emission intensity of major indirect carbon emission units of 5 WWTPs.

In terms of influent water quality, requirements of nitrogen removal could be satisfied. Thus,the process did not need to add carbon source. However, the influent total phosphorus (TP)indicators were affected by industrial water. The current biological phosphorus removal auxiliary dosing phosphorus removal were adopted to achieve effluent discharge standards. For the phosphorus removal agent dosing, a fixed amount of daily dosing cannot effectively control the consumption of pharmaceuticals.

According to the operation and management of the current situation of WWTP A, energy saving and transformation of the main needed to solve the following problems. First, the aeration blower was currently manually operated. Aeration cannot be accurately controlled. Second, foreign industrial sewage on the biochemical system had a certain impact, and the water TP index fluctuations were relatively large. At present, the dosage control of phosphorus remover generally adopted the method of constant dosage, and it was impossible to select the best dosage for automatic dosage according to the parameters of influent water flow and water quality, which was easy to waste the chemicals and affect the activity of sludge. Third, equipment without electricity metering device may be unable to analyze the energy consumption of the equipment. Four, the process operation data was limited by space and could only be obtained from the central control room, thus the management personnel cannot understand the operation condition in time, and the process operation data could not be digitized and analyzed in time.

According to Figure 7(b), the indirect carbon emissions of WWTP A were mainly concentrated in the sewage lifting pumps, centrifugal blowers, submersible actuators, phosphorus removers and return sludge pumps. Combined with the problems existing in the operation of the WWTP, this study focused on the energy saving and emission reduction renovation for the units of sewage lifting pumps, centrifugal blowers and phosphorus remover dosing.

3.3.1. Energy efficiency analysis of sewage lift pumps

The unit sewage power consumption of the sewage lifting pumps of WWTP A was 0.214 kW·h/m^3, which was the highest unit consumption of sewage lifting pumps among the five typical WWTPs. The sewage lifting pumps were mainly divided into 4 units within the WWTP and 11 units outside the WWTP, and frequency conversion speed control technology for energy saving had been adopted, but lifting pumps still cannot achieve remote control.

Specific energy-saving measures for sewage lifting pumps may be carried out from the following aspects. On one hand, intelligent remote control lifting pump had been considered. In the frequency control technology, in order to realize the electrodeless speed regulation of the motor, the sewage lifting pump was always running in the high-efficiency zone, and the Programmable Logic Controller (PLC) system was used to control the frequency converter, so that the sewage lifting pump operated conditions with the changes in the amount of water inlet changes. On the other hand, the daily management and regular maintenance of the pump were strengthened. Timely maintenance and overhaul could improve the efficiency of the pump and maintain efficient work.

3.3.2. Energy saving analysis of aeration system

Aeration system was the key of energy saving of WWTP A, mainly from the new aeration optimization control system to achieve energy saving and consumption reduction. The main optimization of aeration control, reducing energy consumption and carbon loss had been considered. The new aeration control system included new on-line instrumentation of the biological pool, real-time monitoring of ammonia nitrogen, total nitrogen, TP and other states, electric control valve of the biological pool aeration pipe, air gauge and pressure gauge and PLC control system. In this system, the new on-line monitoring instrumentation was used by the new biological pool to monitor the water quality and water quantity. In this system, the new aeration control PLC to collect the incoming water flow Q, COD and ammonia nitrogen concentration and other parameter signals, were sent to the expert library server by the upper computer of the OLE for Process Control (OPC) service. The signals of dissolved oxygen concentration, valve opening and dry pipe flow were collected in the aerobic unit, and the valve opening needed to reach the optimal value of dissolved oxygen was calculated as well as the opening of the electric ball valve was adjusted. At the same time, the flow and pressure signals of the dry (branch) pipe was collected and sent to the Machine Control Panel (MCP) control cabinet of the blower to control the grouping operation and the opening adjustment in order to realize the precise control of the aeration volume.(Figure S1)

To analyze the energy-saving effect, according to the production report of WWTP A, August 2021-August 2022 was taken as the implementation period of the aeration optimization control system, and the same period of 2020-2021 was selected as the comparison period for the statistics of energy consumption of the aeration system. From Table 1, it could be seen that after the implementation of the precise aeration system, a decrease of 19.50% in the power consumption of the blower per unit of water volume and a decrease of 19.35% in the power consumption per unit of OCTP were realized.

3.3.3. Energy efficiency of pharmaceuticals

Energy-saving measures for phosphate removal agent were mainly paid attention to the use of intelligent dosing system. Automatic control of dosing process equipment was achieved, and manual workload was replaced. According to the inlet and outlet water quality to achieve accurate dosing, the level of control was improved and drug consumption was reduced, leading to achieve the precise dosage of pharmaceuticals.

Table 1. Comparison of blower electricity unit consumption between the implementation period and the comparison period

Electricity consumption per unit of sewage				
Items	Unit	Implementation period	Comparison period	Decline rate
Total water intake	m^3	26124308	19969808	/
Calculated value of blower energy consumption	Kw· h	1175736	1116705	/
Energy consumption of blower for tons of water	kW· h/m^3	0.0450	0.0559	19.50%
Reduction of power consumption per unit of OCTP				
Items	Unit	Implementation period	Comparison period	Decline rate
Ozone-depleting pollutant reductions	kg	5082601	3893083	/
Calculated value of blower energy consumption	kW· h	1175736	1116705	/
Blower energy consumption per unit of OCTP	kW· h/kg	0.2313	0.2868	19.35%

Table 2. Drug consumption (liquid) per ton of water produced during the implementation period and the comparison period

Drug consumption per unit of effluent				
Items	Unit	Implementation period	Comparison period	Decline rate
Total water intake	m^3	26124308	19969808	/
Total dosage	kg	1828100	1470620	/
Drug consumption per ton of water	kg/m^3	0.0699	0.0736	5.03%
Reduction of drug consumption per unit of TP				
Items	Unit	Implementation period	Comparison period	Decline rate
TP reduction	kg	108461	83712	/
Total dosage	kg	1828100	1470620	/
Reduction of drug consumption per unit of TP	kg/kg	16.8549	17.5676	4.06%

From Figure S2, phosphate analyzer was added at the water outlet of biochemical pool to determine the phosphate concentration in real time before the dosing point and the phosphate concentration in the water outlet after phosphorus removal. The dosing pump adopted frequency conversion control to adjust the dosage in real time and the flowmeter was added on the dosage pipeline.

Figure 8(a) showed a comparison of the distribution of effluent TP concentration before and after the transformation, it can be seen that the effluent TP fluctuated greatly in the range of 0.1-0.45 mg/L in the comparison period and regularly in the range of 0.15-0.35 mg/L in the implementation period. Combined with the frequency distribution graph and the variance, it can be seen that in the comparison period. Then, the effluent TP was always controlled at a lower value, which reflected the phenomenon of overdosing. While in the implementation period, the TP concentration was mostly in the range of 0.2-0.3 mg/L, which presented the reduction of the dosing cost.

To summarize, after the implementation of the above energy-saving and carbon reduction renovation worked at the WWTP A, the energy saving and carbon reduction results had been remarkable. The indirect carbon emissions of WWTP A had been significantly reduced after its completion and operation. Taking the blower power consumption as well as the TP removal drug consumption from August 2021 to August 2022 as the benchmark, its indirect carbon emissions were calculated, and the comparison found that the indirect carbon emissions were reduced by a total of about 4.405 million tons. After the implementation of the optimized control system, the system automatically according to the water load and the current operating conditions automatically started and stopped the blower, greatly reducing the labor intensity of the operators. Abouts 80% of the process unit achieved unmanned production, leading to effectively reduce operating costs on-site duty and inspection. Furthermore, maintenance staffing could be reduced by about 20% compared with before the transformation, saving labor costs of nearly 600,000 yuan.

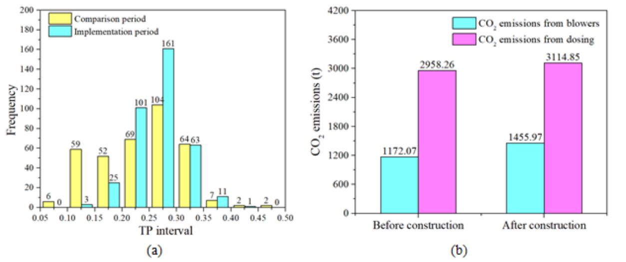


Figure 8. (a) Comparison of TP concentration distribution zones of effluent before and after modification; (b) comparison of indirect carbon emissions before and after energy saving and consumption reduction in plant A.

4. Conclusion

Based on the design scale, treatment process and construction form, five typical WWTPs were selected for the study. The energy consumption components of the WWTPs were evaluated in terms of electrical and pharmaceutical consumption, respectively. The results showed that the electricity consumption per unit of effluent in the WWTPs showed a tendency to decrease with the increase of the operating load factor. In addition, the dosing levels of carbon source, phosphorus remover, disinfectant and sludge flocculant confirmed that pharmaceutical consumption was also one of the important energy consumptions in WWTPs. Next, the indirect carbon emissions of the five WWTPs were ranked as A > D > B > E > C. Carbon emissions due to electrical energy consumption were the most important source of indirect carbon emissions in the WWTPs. The intensity of indirect carbon emissions in the five WWTPs was mainly concentrated in the aeration blowers, effluent lifting pumps, submersible thrusters, phosphorus removers and return sludge pumps in the biological treatment units. Combined with the problems existing in the operation of the WWTP A, the focus was on the sewage lifting pumps, centrifugal blowers and phosphorus remover dosing units to carry out energy-saving and emission reduction renovation. After the transformation the operating costs was reduced by about 20%, saving labor costs of nearly 600,000 yuan.

5. Notes

The authors declare no competing financial interest.

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Text S1 Analysis of the current situation

According to the design scale, there were 14 plants with a design scale of 1-20,000 t/d, accounting for about 19.2%; 31 plants with a design scale of 2-50,000 t/d, accounting for about 42.5%; 23 plants with a design scale of 50-100,000 t/d, accounting for about 31.5%; and 5 plants with a design scale of more than 100,000 t/d, accounting for about 6.8%, so that the WWTPs with a design scale of 2-10,000 t/d accounted for 74.0% of the sewage treatment plants. 100,000 t/d accounted for 74.0% of the wastewater treatment plants and 20,000-100,000 t/d was the most common treatment size of the wastewater treatment plants.

According to the treatment process, about 44.3% of urban domestic wastewater treatment plants in Chongqing chose A2O process, about 34.1% of oxidation ditch process, about 10.2% of CASS/CAST process, about 5.7% of SBR process, about 2.3% of aeration bio-filter process and about 3.4% of A2O+MBR process. Therefore, the sewage treatment plants using A2O and oxidation ditch process accounted for 78.4% of the urban sewage treatment plants. A2O and oxidation ditch were the most commonly used treatment processes in the urban sewage treatment plants.

According to the construction form, There was only one sewage treatment plant in Chongqing with an underground layout for urban domestic sewage treatment plants, and the remaining 72 were conventional above-ground sewage treatment plants, accounting for about 98.6% of the total number of plants. In recent years, in the face of conventional above-ground sewage treatment plant covers an area of large, serious neighbor avoidance effect and other practical problems, underground sewage treatment plant due to environmentally friendly, small footprint, can lead to improve the quality of the surrounding land. Thus, above-ground sewage treatment plant and underground sewage treatment plant for the urban sewage treatment plant commonly used forms of construction.

Table S1. Basic information of a typical sewage treatment plant

No.	Design Scale (104t/d)	Effluent standard	Treatment process	Disinfection method	Sludge process	Deodorization process	Forms of construction
A	10	Level 1A	A_2O	Liquid chlorine	Belt dehydration	/	On the ground
B	5	Level 1A	A_2O	Ultraviolet ray	Centrifugal dehydration	biological deodorization	Under the ground
C	2	Level 1A	Oxidation ditch	Chlorine dioxide	Belt dehydration	biological deodorization	On the ground
D	6	Level 1A	A_2O	Chlorine dioxide	Belt dehydration	biological deodorization	On the ground
E	5	Level 1A	A_2O	Chlorine dioxide	Belt dehydration	/	On the ground

Table S2. Chemical emission factors

Type	Consumables	Emission factors(kg CO_2-eq/kg)
Phosphorus removal agent	Ferrous sulfate	0.6
	Polymeric aluminum chloride	0.53
	Aluminum-iron composite[a]	0.6
	$FeSO_4$	0.26
	Ferric chloride	0.93
	Calcium oxide	1.1
	Aluminum sulfate	0.16
Dewatering agents	Polyacrylamide	1.48
Disinfectant	Hydrochloric acid	1.2
	Sodium chlorate or sodium chlorite[a]	1.1
	Liquid chlorine	1.1
	Sodium hypochlorite	0.99
	Disinfectant powder[a]	1.1
	O_3	11.36
Additive carbon source	Edible glucose[a]	0.7
	Sodium acetate	0.623
	Wood spirit	0.61
	Other carbon sources[a]	0.7
	Acetic acid	0.852

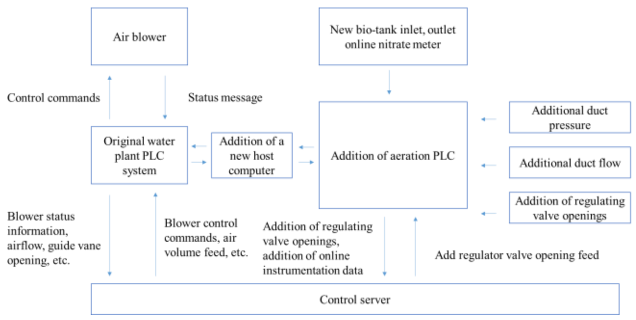

Figure S1. Aeration automatic control system structure

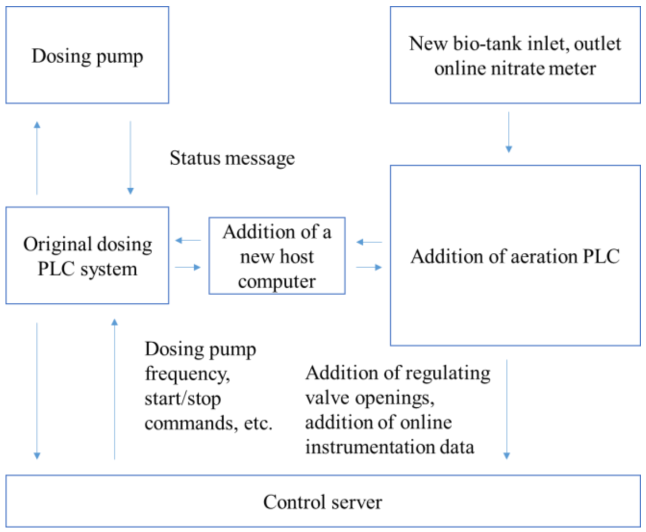

Figure S2. Phosphorus removal automatic control system structure.