Global NEST Journal, Vol 27, No 6, 07245

A case study on the upgrading and reconstruction of a wastewater treatment plant in Hebei Province

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Received: 03/01/2025, Accepted: 09/05/2025, Available online: 23/05/2025
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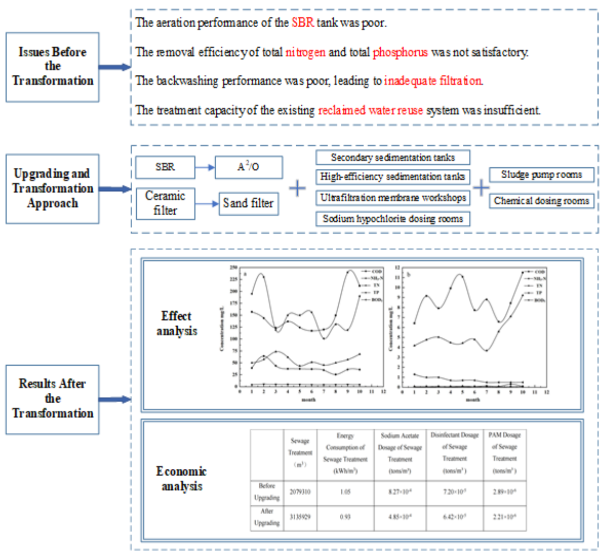
https://doi.org/10.30955/gnj.07245

Graphical abstract



Abstract

The effluent quality of a wastewater treatment plant (WWTP) in Hebei Province met the Class I-A standard of "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants"(GB 18918-2002) (COD≤50 mg/L, TN≤15 mg/L, TP≤0.5 mg/L, NH_3-N≤8 mg/L). However, under the guidance of energy conservation and emission reduction, existing WWTP were faced with some limitations, such as ineffective phosphorus and nitrogen removal, and upgrading treatment standards were required. Existing facilities are fully used and the synergistic strategy of enhancing biological efficiency and deepening treatment processes are adopted to achieve reduction of pollutants such as organics, nitrogen and phosphorus. The results show that the removal rates of COD, NH_3-N, TP and TN reaches 94.6%, 99.8%, 86.5% and 98.0% respectively, even with the influent flow having increased by 50.8%, enabling the effluent to meet strict discharge standards (Class B standard of Beijing's "Comprehensive Discharge Standard for Water Pollutants") (DB11/307-2013) (COD≤40 mg/L, TN ≤ 15 mg/L, TP≤0.4 mg/L, NH_3-N≤5mg/L). Electricity consumption decreases by 11.4%, and the usage amounts of sodium acetate, disinfectant, and polyacrylamide respectively decrease by 41.4%, 10.8%, and 23.5%. This project significantly improves the local environment and protects downstream ecosystems. It provides valuable reference insights for similar WWTPs.

Keywords: Wastewater treatment plant; upgrading and reconstruction; multi-stage anaerobic-anoxic-oxic; sand filter; ultrafiltration

1. Introduction

In contemporary society, with the rapid economic development and the accelerating process of urbanization, water pollution has emerged as a growing issue, becoming one of the key challenges to sustainable development (Zhang, 2023). Particularly within the national strategy of coordinated development in the Beijing-Tianjin-Hebei region, Hebei Province is a key link and its efforts in industrial pollution control and environmental protection are important. The WWTP in Hebei receives wastewater containing significant concentrations of refractory COD compounds. Recent studies have highlighted that 56% of industrial wastewater in developing countries contained refractory COD components resistant to conventional biological treatment, driving demand for advanced oxidation and membrane technologies (Jin *et al*., 2022). This aligns with global trends where the adoption of membrane bioreactor technology (MBR) has significantly increased in recent years, markedly improving COD removal efficiency in industrial applications (Al-Asheh *et al*., 2021). The anaerobic-anoxic-oxic (A^2/O)-MBR process integrates anaerobic, anoxic, and aerobic treatment stages with membrane bioreactor technology, significantly improving COD removal efficiency in wastewater and enhancing system resistance to shock loads (Zhou *et al*., 2022).

The effluent quality of a WWTP in Hebei Province met the Class I-A standard of "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants". However, there were still several issues during the operation, such as the poor treatment capacity of the fine screen and vortex grit chamber, the undesirable aeration effect and short retention times in the sequencing batch reactor (SBR) tank, poor backwashing and filtration performance, the unstable reuse of treated water, the increasing expected demand for recycled water the insufficient treatment capacity of current water reuse system and the inadequate phosphorus and nitrogen removal effect. Based on the comparison between the current effluent quality and the target water quality after the upgrading, the core focus of this renovation is to enhance the biological treatment efficiency, particularly for the effective removal of COD, NH_3-N, TN and TP. Therefore, multi-stage A^2/O is adopted. Compared with other processes (such as the activated sludge process, oxidation ditch process, SBR process, and MBR process), the multi-stage A^2O process demonstrates significant advantages in terms of nitrogen and phosphorus removal efficiency, impact load resistance, sludge stability, and operational flexibility, thanks to its unique multi-stage structure, precise environmental control, and diverse microbial community (Abma *et al*., 2010 and Ahn *et al*., 2020). Additionally, a deep treatment unit is added to strengthen the management and control of both wastewater and sludge. The goal is to improve effluent quality from the national Class I-A standard to the stricter Class B discharge limits in the Beijing "Comprehensive Emission Standard for Water Pollutants" (DB11/307-2013). At the same time, the project also focuses on resource recovery and reuse. By reducing, stabilizing, and harmlessly treating sludge, the project has achieved the resource utilization of sludge, thus reducing the risk of secondary pollution (Shao *et al*., 2021 and Liu *et al*., 2022). This action shows the company ’s responsibility to society and is a key step in improving regional environmental quality (Zhang *et al*., 2023).

The implementation of this project has significant implications for improving the local natural environment and safeguarding the health of the downstream ecosystem (Guo *et al*., 2023). As pollutant emissions are substantially reduced, the water quality of regional rivers will improve significantly. This not only beautifies the urban landscape but also provides a better habitat for aquatic life, thereby promoting the restoration and protection of biodiversity. In addition, a healthy water environment can attract more tourists and investors, boosting the development of local tourism and related industries. This, in turn, injects new vitality into the region’s green and sustainable economic growth (Tomei *et al*., 2016 and Tang, 2022). The construction of this project will significantly reduce the total amount of pollutants discharged into water bodies, ensuring effective pollution control. As a result, it will lead to a marked improvement in the water quality of regional rivers, thereby laying a solid and reliable foundation for the green and sustainable growth of the regional economy (Xu, 2019). The implementation of this project has markedly enhanced the ability to decrease pollutants, drastically lowered the overall pollution levels, and led to a significant improvement in water quality and the plant's economic operational efficiency and sustainability. It serves as a valuable reference for comparable WWTPs.

2. Material and methods

2.1. Overview of the WWTP before the upgrading

The original design capacity of the WWTP in Hebei Province was 60,000 m^3/d, while the actual inflow was approximately 41,700 m^3/d, based on a 95% coverage rate. The treatment process included pre-treatment, biochemical SBR, filtration, and disinfection, as shown in **Figure 1**. After treatment, the water quality met the Class I-A standard of "Discharge Standards of Pollutants for Municipal Wastewater Treatment Plants,"(GB 18918-2002) as detailed in **Table 1**.

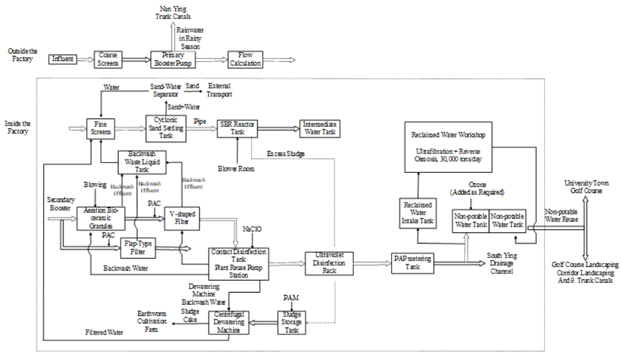


Figure 1. Engineering process flow before upgrading

Table 1. Inlet and outlet water quality of WWTP before upgrading

Project	COD mg/L	BOD_5 mg/L	NH_3-N mg/L	TN mg/L	TP mg/L	pH
Influent Index	400	200	25	65	4.0	6~9
Effluent Index	50	10	8	15	0.5	6~9
Removal Rate	87.5%	95%	68%	76.9%	87.5%	/

2.2. Approach of upgrading and renovation of the WWTP

2.2.1. Overall technical approach for the renovation

The strategy of combining optimized biological treatment with advanced treatment is adopted, aiming to further purify the water and effectively remove various pollutants such as organic matter, suspended solids, nitrogen, and phosphorus. The design concept is as follows:

(1). An enhanced biochemical treatment is used to better remove BOD_5, COD, NH_3-N, TN, TP. Since the influent has a BOD_5/TN ratio<4, showing a carbon source shortage (Yao *et al*., 2018), carbon supplementation is added in the anoxic tank. The influent BOD_5/TP ratio is 50 (200/4), meeting basic biological phosphorus-removal conditions, but with unstable results. So chemical phosphorus removal is added. Adding iron or aluminum salts makes phosphate ions form precipitates, which are removed by physical filtration. Influent TN is mainly NH_3-N and NO_3-N, removed by biochemical reactions in the biological tank. When the tank reaches capacity and TN remains, a denitrification unit is added in deep treatment (Gu *et al*., 2024). Under anoxic conditions, heterotrophic bacteria uses influent organic matter or extra carbon sources (like methanol or sodium acetate when needed) to break down NO_3-N, reducing TN further and improving effluent quality. Moreover, the deep treatment process, such as high-efficiency sedimentation tanks, filter tanks, and ultrafiltration systems, is adopted to reduce TP, while maintaining the original disinfection process to ensure stable and compliant effluent quality.

(2). The removal of total coliforms primarily relies on effective physical and chemical disinfection methods, such as chlorination and ultraviolet disinfection. In this study, sodium hypochlorite disinfection is used.

In summary, the wastewater treatment process adopted in this study is a combined process of coarse and fine screens + aerated grit chamber + multi-stage anaerobic-anoxic-oxic (A^2/O) + secondary sedimentation tank + high-efficiency sedimentation tank + filter tank + disinfection (Yue *et al*., 2024, Li *et al*., 2020, Yu *et al*., 2023 and Qiao *et al*., 2024), as shown in **Figure 2**, aiming to achieve stable and compliant water quality under typical operating conditions. Briefly, the sewage treatment process starts with raw sewage passing through a coarse screen to remove large debris, then flowing to the external lift pump station's collection well and being pumped to the treatment plant's influent gate well. It goes through a fine screen and an aerated grit chamber. Next, it enters multi-stage A^2/O tanks where the carbon source cuts aeration needs for organic pollutant removal (Lu *et al*., 2024; Wang *et al*., 2023). After that, the effluent from the secondary sedimentation tank goes to a high-efficiency sedimentation tank for phosphorus removal, followed by deep treatment and disinfection through various filters. Treated water is either discharged into the Nanying drainage channel or sent for reuse via the reclaimed water and ultrafiltration workshops. Wastewater from filtration is recycled back to the grit channel for re-treatment.

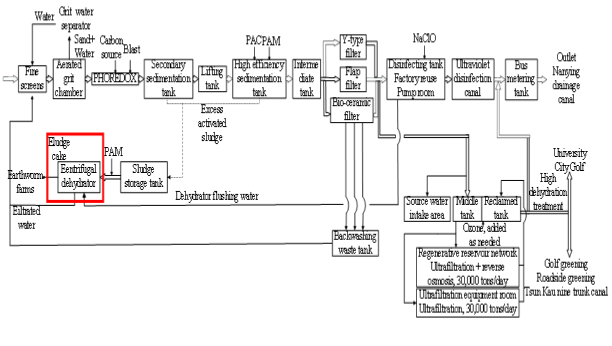


Figure 2. Process flow of upgrading and reconstruction project

2.2.2. *Biological tank renovation*

Biological treatment utilizes the metabolic action of microorganisms to degrade organics in wastewater. This method boasts advantages such as effective treatment and low cost, and is widely applied in fields such as municipal wastewater treatment, industrial wastewater treatment, even in marine waters (Sayed *et al*., 2021). The SBR biological tank is transformed into a multi-stage A^2/O tank type, utilizing the existing civil tank structure by adding partitions and creating openings in the existing partitions. The design capacity of the biological tank is 60,000 m^3/d, with a total variation coefficient of 1.0. It is divided into 2 series and anaerobic, first anoxic, first aerobic, degassing, second anoxic, and second aerobic are included. The effective water depth is 5 meters, with a design minimum water temperature of 15° C and a maximum of 25° C. The anaerobic section, first anoxic section, first aerobic section, degassing section, second anoxic section, second aerobic section has a retention time of 2 hours, 3.9 hours, 9.6 hours, 0.5 hours, 2.5 hours, and 1 hours, respectively. The sludge concentration is 3,400 mg/L, with an internal recycle ratio of 400% and an external recycle ratio of 100%. The design sludge age in the aerobic zone is 7 days. There are 9 internal recycle pumps, with 8 in operation and 1 in reserve. The anaerobic, first anoxic, and second anoxic zones are equipped with 12, 16, and 8 underwater low-speed agitators, respectively. The aeration capacity is 6,542.8 m^3/h, with micropore aerators in the aerobic zones, each providing 3 m^3/h of air.

2.2.3. *Expansion of ceramic granule filter tank*

The inlet and outlet piping of the ceramic granule filter tank remains unchanged. In the distribution channel, a DN400 inlet hole and manual/electric gate valve is added to each filter tank. Each filter tank's inlet channel is separated by a partition wall, with the wall height extending to the top plate of the inlet channel. Each inlet pipe made of stainless steel 304L is equipped with a DN300 manual/electric regulating butterfly valve and a pressure sensor. The filter media in each filter tank is replaced from ceramic granules to quartz sand.

2.2.4. *Construction of secondary sedimentation tank, sludge pump room, and high-efficiency sedimentation tank*

The secondary sedimentation tank, sludge pump room, and high-efficiency sedimentation tank are constructed together, with a total variation coefficient of 1.3, and divided into 2 series. The total land area for the secondary sedimentation tank and sludge pump room is 1,371.52 m^2, and the area for the high-efficiency sedimentation tank and equipment room is 157 m^3. The secondary sedimentation tank will be a horizontal-flow type with a peripheral inlet and peripheral outlet and water depth is 4.5 meters, with a nominal sedimentation time of approximately 4.12 hours. The actual retention time is 2.06 hours and 1.79 hours at design flow, respectively. The effluent is collected using a double-sided triangular weir rectangular collection tank, with a chain scraper mechanism installed in each tank.

The sludge pump room is equipped with 3 return sludge pumps, with 2 in operation and 1 in reserve, and 2 excess sludge pumps, with 1 in operation and 1 in reserve. The design capacity of the high-efficiency sedimentation tank is 60,000 m^3/d, with a total variation coefficient of 1.3 and consisted of 2 sets, with each set comprising a mixing tank, flocculation tank, sedimentation tank, inclined tube separator, effluent channel, and sludge recycling system.

The effluent from the secondary sedimentation tank flows through a B=1m channel into the inlet channel of the high-efficiency sedimentation tank, where it is divided into two groups and entered the respective mixing tanks via separate weirs. Each mechanical mixing tank is equipped with one mechanical agitator, one dosing pipe, and one return sludge pipe. After mechanical mixing, the coagulant and return sludge are thoroughly blended with the wastewater, forming flocs that enters the flocculation tank, which is equipped with one set of cylindrical flocculation stirrers. The flocculated wastewater then enters the sedimentation tank, which is equipped with one scraper at the bottom and an inclined tube separator, effluent weir, and collection channel at the top. The effluent from both sedimentation tanks converges in the effluent main channel and flows through a DN800 pipeline into the intermediate water pool.

2.2.5. Construction of new ultrafiltration membrane workshop and sodium hypochlorite dosing room

Sodium hypochlorite (10%) is used for disinfection, and the maximum dosing rate is 100 mg/L. 3 storage tanks made of high density polyethylene material are designed for a 7-day supply. Each storage tank is equipped with one set of a hinged liquid level gauge, totaling 2 sets. Additionally, one chlorine leakage alarm is equipped in the sodium hypochlorite dosing room.

2.2.6. Construction of new dosing room

The dosing room, occupying an area of 177.74 square meters, is primarily used for the chemical phosphorus removal through the addition of 25% liquid polyaluminum ferric chloride. The phosphorus removal dosing points are located in the mixing tanks of the high-efficiency sedimentation pool, with a total of two points. During the dosing process, the chemical solution is diluted online to a concentration of 5% after passing through the pump. To ensure continuous operation, the chemical dosage is calculated based on a seven-day reserve and stored in two tanks made of HDPE material.

The dosing system is equipped with four diaphragm metering pumps, three of which are in normal use and one was on standby, with provisions for future pump additions. To monitor the liquid level of the chemical solution in the tanks, each tank is installed with a set of tilting level gauge, totaling two sets. Additionally, a sodium acetate storage tank is set up, which is divided into two independent sections with a storage capacity designed for ten days of use. Each storage section has a width of 5.5 meters, a length of 4 meters, and an effective water depth of 2.7 meters.

2.3. Monitoring of effluent water quality after the upgrading process

Online monitoring equipment is installed to conduct real-time monitoring of the main effluent water quality indicators, such as COD, NH_3-N, TP, TN, etc. These devices can continuously collect water samples and perform rapid analysis, and transmit the data to the monitoring center in real time, so as to timely understand the changes in water quality.

2.4. The energy-saving technologies of the WWTP

The energy-saving technologies of the WWTP are mainly manifested in the following aspects: a reasonable treatment process, a high-efficiency overall design, and energy-saving equipment. Firstly, the multi-stage A^2/O treatment process, featuring staged influent, rationally distributes the influent points and influent volume. This approach maximizes the utilization of carbon sources in the wastewater, effectively cutting down the quantity of organic pollutants that need to be removed through aeration. Secondly, the forms of water inlet and outlet of the structures and the connection forms between pipelines are rationally designed to reduce the head loss in the WWTP. The layout of the structures and pipelines is made as compact and simple as possible to avoid unnecessary turns and long-distance transportation. These methods effectively reduce the lifting head of the sewage treatment plant and greatly reduce the direct energy consumption.

In summary, the WWTP is expected to achieve remarkable improvements. In terms of effluent quality, the enhanced treatment process will ensure that the treated water meets more stringent environmental standards, reducing the negative impact on the surrounding water bodies. Regarding operational efficiency, the reduction in lifting head and energy consumption will not only cut down the operating costs but also improve the overall reliability and stability of the treatment system. These improvements will make the WWTP more sustainable and environmentally friendly, better serving the community and protecting the ecological environment.

3. Results

3.1. Operational performance and analysis

After the completion of the upgrading of wastewater treatment plant, all equipment and treatment units have operated stably, and the effluent quality has consistently met the expected design standards. Continuous 24-hour monitoring water quality of influent and effluent is conducted, and the online monitoring results in October 2023 are shown in **Table 2**. The monthly influent and effluent quality from January to October is presented in **Figure 3**. The average influent concentrations of COD, NH_3-N, TP and TN are 211.69 mg/L, 35.93 mg/L, 68.35 mg/L, 4.42 mg/L; the average effluent concentrations are 11.51 mg/L, 0.06 mg/L, 9.23 mg/L, 0.09 mg/L. The removal rates of COD, NH_3-N, TP and TN are 94.6%, 99.8%, 86.5%, 98.0% respectively. All indicators have remained within the B-level standards specified in the Beijing "Comprehensive Discharge Standards for Water Pollutants" (DB11/307-2013). The improvements in effluent quality can be attributed to the enhanced efficiency of the newly installed A^2/O biological treatment process.

This remarkable achievement in wastewater treatment has far-reaching environmental implications. Firstly, it can effectively minimize the pollution of surface water by sewage. Reducing the amount of pollutants discharged into surface water bodies helps to maintain the ecological balance of rivers, lakes, and other water sources. Secondly, it plays a crucial role in improving the local natural environment. Cleaner water bodies lead to a more pleasant and healthy living environment for local residents, enhancing the overall aesthetic and ecological value of the area. Finally, it also serves to protect the downstream ecological environment. By ensuring that the effluent is of high quality, the risk of downstream water pollution and ecological damage is greatly reduced, safeguarding the habitats of various aquatic organisms and promoting the sustainable development of the entire ecological system.

Table 2. Monitoring data of inlet and outlet water quality in October 2023

Time/Day	pH		COD mg·L^{-1}		NH_3-N mg·L^{-1}		TN mg·L^{-1}		TP mg·L^{-1}	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	7.45	6.86	202.04	11.65	33.33	0.06	77.78	10.80	3.75	0.03
2	7.20	6.93	328.08	10.91	30.90	0.06	56.47	9.27	3.56	0.04
3	6.79	6.97	241.13	10.84	30.11	0.05	64.00	8.52	4.33	0.05
4	7.37	6.96	195.68	10.88	33.21	0.06	77.19	9.36	4.23	0.08
5	7.43	6.89	162.87	9.44	31.19	0.06	80.98	9.86	4.42	0.16
6	6.86	6.85	135.93	5.84	28.26	0.06	51.91	10.57	4.78	0.17
7	6.46	6.80	311.91	5.86	31.08	0.07	49.09	10.29	5.75	0.15
8	6.81	6.77	332.99	7.26	32.31	0.05	59.64	10.35	5.84	0.16
9	7.35	6.77	203.19	8.60	31.11	0.06	64.32	9.65	4.96	0.16
10	6.92	6.73	224.67	8.56	33.31	0.06	70.59	8.57	4.58	0.14
11	6.15	6.71	223.22	9.22	30.12	0.06	57.30	8.44	4.48	0.11
12	6.70	6.69	194.83	8.22	35.36	0.06	56.88	7.82	4.47	0.10
13	6.99	6.54	182.92	8.69	39.37	0.05	57.66	8.32	4.71	0.11
14	6.92	6.66	195.44	8.85	37.94	0.06	54.33	8.70	4.45	0.08
15	6.83	6.71	220.08	14.37	39.12	0.06	61.81	8.00	4.66	0.08
16	6.88	6.69	218.53	9.00	39.45	0.06	68.03	7.84	4.62	0.07
17	6.87	6.67	200.92	9.50	43.20	0.05	70.07	8.03	4.71	0.07
18	6.93	6.67	189.33	15.62	39.98	0.06	61.19	8.84	4.71	0.06
19	7.02	6.76	203.26	7.27	40.48	0.06	65.88	8.45	4.21	0.11
20	6.98	6.84	197.66	12.74	37.97	0.06	102.77	9.37	3.95	0.10
21	6.94	6.78	166.45	12.05	34.36	0.06	66.64	7.53	3.67	0.08
22	6.88	6.76	197.72	12.04	37.94	0.06	63.70	9.57	3.97	0.04
23	6.78	6.76	165.84	13.20	35.71	0.06	94.88	9.77	3.89	0.04
24	6.94	6.73	165.25	14.64	36.72	0.06	84.85	9.75	3.91	0.04
25	6.90	6.72	188.46	15.21	38.34	0.08	89.21	9.95	3.99	0.04
26	6.90	6.78	208.18	15.72	37.86	0.05	90.99	9.79	4.07	0.05
27	6.84	6.80	225.20	16.54	38.30	0.06	60.22	10.28	4.35	0.06
28	6.82	6.79	227.92	16.48	37.95	0.06	63.27	10.40	4.38	0.07
29	6.91	6.78	255.75	14.94	39.31	0.07	41.50	9.21	4.41	0.08
30	6.88	6.77	199.54	16.86	38.01	0.06	70.97	8.91	4.55	0.10
31	6.99	6.77	197.53	15.73	41.41	0.05	84.88	9.80	4.59	0.10
Average	6.93	6.77	211.69	11.51	35.93	0.06	68.35	9.23	4.42	0.09

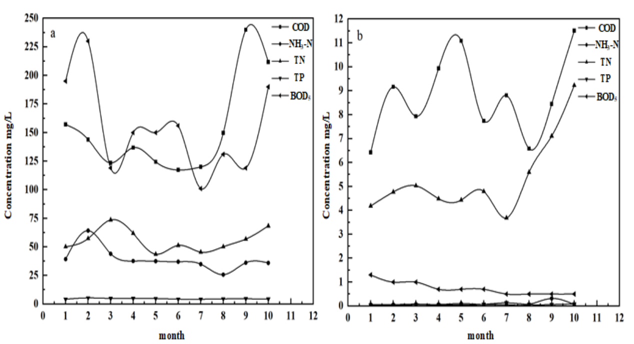


Figure 3. Monthly influent (a) and effluent (b) quality of the WWTP from January to October 2023

3.2. Energy efficiency analysis of the treatment process

Firstly, the multi-stage A^2/O treatment process maximizes the utilization of carbon sources in the wastewater, effectively reducing the amount of organic pollutants that required aeration for removal. Due to the optimization of the A^2/O process, energy consumption is reduced by 20%. This, in turn, reduces energy consumption, achieving efficient resource utilization and energy savings. Secondly, the compact process and simple and efficient pipeline connections significantly shortens the water flow path and reduced hydraulic losses, which lowers the head requirements for the influent pumps, allowing them to better adapt to fluctuations in water volume, thereby reducing operational costs. Thirdly, the selection of identical model equipment combinations ensures flexible and rational operation under varying flow conditions, contributing to energy savings. In addition, high-efficiency models are used for both wastewater pumps and sludge pumps, which maintains an efficiency of no less than 60%, further enhancing overall energy efficiency. Finally, the treated effluent is reused in some areas such as landscape irrigation, vehicle washing, road cleaning, and backwashing of dewatering machines, which significantly reduces the consumption of tap water and achieved the recycling of water resources.

3.3. Economic benefit analysis

Due to changes in the costs of electricity and chemicals during the plant's upgrading process, the direct cost comparison has lost its original baseline. To more scientifically assessed its economic benefits, a comparative analysis of electricity consumption and chemical usage is conducted (see **Table 3**). As shown in **Table 3**, the electricity consumption of sewage treatment before and after the renovation is 1.05 kWh/m^3, 0.93 kWh/m^3, revealing an 11.4% reduction in electricity consumption after the upgrade. Moreover, the consumption of chemicals such as sodium acetate, disinfectant, and polyacrylamide (PAM) decreases by 41.4%, 10.8%, and 23.5%, respectively. Overall, after the completion of the upgrading, the WWTP not only improves its treatment efficiency but also achieves a significant reduction in the amount of electricity and chemicals. This has significantly enhanced the plant's economic operational efficiency and sustainability.

Table 3. Comparative analysis of electricity consumption and the amount of chemicals before and after the upgrading and reconstruction during 1-3 months

	Sewage Treatment (m$^{3)}$	**Energy Consumption of Sewage Treatment (kWh/m^3)**	**Sodium Acetate Dosage of Sewage Treatment (tons/m^3)**	**Disinfectant Dosage of Sewage Treatment (tons/m^3)**	**PAM Dosage of Sewage Treatment (tons/m^3)**
Before Upgrading	2079310	1.05	8.27×10^{-4}	7.20×10^{-5}	2.89×10^{-6}
After Upgrading	3135929	0.93	4.85×10^{-4}	6.42×10^{-5}	2.21×10^{-6}
Variation Rate	50.8% increase	11.4% decrease	41.4% decrease	10.8% decrease	23.5% decrease

4. Discussion

WWTPs serve as crucial infrastructure for recycling water resources and safeguarding inland water bodies and coastal ecosystems. Enhancing their pollutant removal capabilities can effectively combat water pollution (Guo *et al*., 2023) and foster greater circularity in water resource management. In China, where these issues are particularly pressing, the Ministry of Ecology and Environment has introduced stricter pollutant discharge standards for WWTPs, aiming to achieve substantial environmental benefits and water quality improvements (Mazhar *et al*., 2021). To comply with these increasingly stringent standards, it is imperative to upgrade WWTPs with additional tertiary treatment processes, such as conventional chemical phosphorus removal, biological nutrient removal (Rahman *et al*., 2016), even advanced treatment technology (Hanafiah *et al*., 2024) or bioremediation for various emerging pollutants (particularly pharmaceutical active compounds) (Sayed *et al*., 2024). Furthermore, assessing the sustainability of WWTPs, including their economic and environmental impacts, is equally important (Kwon *et al*., 2023).

There have been several literature reports on the upgrading and reconstruction of WWTPs. Some analyses of wastewater treatment pathways have tended to concentrate either on traditional processes (Mazhar *et al*., 2021; Rahman *et al*., 2016) or individual constructed wetlands (Cao *et al*., 2021). Studies have employed model simulations to quantify the environmental impacts and economic costs of various WWTP upgrade pathways, aiding in decision-making (Kwon *et al*., 2023; Mucha *et al*., 2016). Similar to these studies, this study aims to enhance the performance of the WWTP. Two primary aspects are considered: ensuring the required effluent quality, and improving the plant's overall energy efficiency and reducing economic costs. The results show that, even when there is a 50.8% increase in influent loading, the treatment plant can treat wastewater effectively. The removal rates of COD, NH_3-N, TP and TN reaches 94.6%, 99.8%, 86.5% and 98.0% respectively, enabling the effluent to meet strict discharge standards.

Additionally, compared to the original process, less energy is required for aeration due to the maximized utilization of carbon sources in the wastewater during the multi-stage A^2/O treatment process. Adopting more energy-efficient equipment and constantly updating and optimizing the treatment process with technological progress can ensure that energy consumption remains at a low level in the long term, which are sustainable. Moreover, boosting the WWTP's energy efficiency cuts its carbon footprint. Using efficient gear and optimizing processes helps. For example, in the biological treatment, high-efficiency pumps and aeration systems lower overall electricity use. As most power comes from fossil fuels, less demand from the plant means less coal, oil, or gas burned at power plants. So, greenhouse gas emissions like CO_2 and CH_4 go down. If an energy-saving upgrade cuts the plant's annual electricity use by 10%, with local grid carbon intensity in mind, it can slash annual CO_2-equivalent emissions by thousands of tons. This betters local air quality and aids the global fight against climate change, a key step for wider environmental goals.

Electricity and chemicals are two of the most significant cost factors in WWTPs (Monje*et al*., 2022). Some research has examined energy consumption patterns in finish WWTPs (Gurung *et al*., 2018), while others have explored the effects of advanced processes on WWTP upgrades, focusing on effluent quality, energy consumption reduction, and operational cost lowering (Foerster *et al*., 2021; Cairone *et al*., 2024). In contrast, they only give a broad range of treatment efficiency improvements without such precise values (Wei *et al*., 2022). This study provides very detailed and specific quantitative data. We have quantified these costs, revealing an 11.4% reduction in electricity consumption after the upgrade. Moreover, the consumption of chemicals such as sodium acetate, disinfectant, and PAM decreases by 41.4%, 10.8%, and 23.5%, respectively. Although some studies focus on common pollutants like COD, NH_3- N, TP, TN and heavy metals (Lian *et al*., 2024), this study also pays attention to the reduction of specific amount of chemicals. A report by the National Development and Reform Commission in 2024 emphasized the importance of considering energy and chemical consumption in wastewater treatment plants. This shows that this study has a more comprehensive perspective on both pollutant treatment and cost-effective operation.

In the long term, decrease in energy and the amount of chemicals benefits its overall operational efficiency. Lower energy use cuts costs like electricity, freeing up money for things like equipment maintenance. This indirectly improves production flow and product quality, thus enhancing overall efficiency. In terms of chemicals, developing low-use chemicals can maintain low chemical consumption and long-term sustainability. Furthermore, the reduction in chemical usage in the WWTP brings multiple benefits to the local ecosystem. Chemicals like coagulants and disinfectants can be dangerous if mismanaged. Optimizing processes or using alternatives cuts chemical residues in discharged water, keeping the water's natural chemical balance. For instance, too much chlorine-based disinfectant makes harmful by-products. Using less chlorine protects aquatic life. Moreover, less usage of chemicals benefits soil and groundwater. If used for irrigation or seeping into groundwater, lower usage of chemicals stop soil contamination and prevent harmful substances from reaching the water table. This creates a healthier soil ecosystem for plants and soil organisms. Overall, reducing usage of chemicals in sewage treatment is crucial for protecting local aquatic, soil, and groundwater ecosystems, which are key parts of the environment.

In conclusion, this study contributes unique aspects to the existing body of knowledge on a WWTP upgrades while also sharing common goals and approaches with other relevant research. These steps can be taken to optimize the system. In energy management, an intelligent energy-monitoring system should be installed to monitor real-time energy use in each production stage, find high-energy-consuming areas, and make targeted improvements. Regarding chemicals, an evaluation system ought to be established to regularly evaluate the necessity of chemical usage and the rationality of the dosage.

5. Conclusion

A comprehensive process chain is adopted, including coarse and fine screening pretreatment + aerated grit removal + multi-stage anaerobic-anoxic-oxic (A^2/O) biological deep treatment + secondary sedimentation + high-efficiency settling and filtration + final disinfection. The results show that this study has a more comprehensive perspective on both pollutant treatment and cost-effective operation. The removal rates of COD, NH_3-N, TP and TN reached 94.6%, 99.8%, 86.5% and 98.0% respectively, enabling the effluent to meet strict discharge standards, effectively reducing the pollution load on the water environment and achieving effective pollution control. Electricity consumption decreases by 11.4% while the consumption of sodium acetate, disinfectant, and PAM decreases by 41.4%, 10.8%, and 23.5% respectively. Furthermore, the plant's operational efficiency and its capacity for operational sustainability have improved significantly, supporting ongoing efforts in pollution reduction and water reuse. This has contributed positively to the improvement of the river water quality in the region. In the future, the scope of resource recovery and utilization can be further expanded. For example, the technologies and methods should be explored for recovering energy (such as methane) from sewage to realize the energy utilization of sewage; or the recovery efficiency of valuable elements such as phosphorus should be improved to achieve the sustainable recycling of resources. Overall, this upgrading project not only enhances the wastewater treatment efficiency but also provides valuable reference and learning opportunities for similar wastewater treatment projects.

Acknowledgments

This research was funded by Science and Technology Project of Hebei Education Department (No. ZC2025080 and QN2024113) and 2024 University-level Graduate Innovation Funding Program (YKY-2024-33).

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