ISSN: 2710-0588

Research on Wastewaterr Reuse Technology in Expressway Service Areas

Kefan Liu[1], Ying Han[1], Shuaipeng Yang[1], Kun Li[2], Dong Li[2]

[1]College of Civil and Architectural Engineering, North China University of Science and Technology, Tangshan 063200, China

[2]Xinjiang Transportation Planning Survey and Design Research Institute, Urumchi 830000, China

Abstract

This article analyzes the literature and data on reclaimed water research in expressway service areas in recent years. Based on the characteristics of wastewater in service areas and the problems in the treatment process, a comprehensive analysis is conducted on the existing technologies for reclaimed water reuse technology in expressway service areas. It is found that research on carbon emissions from wastewater treatment in service areas and the practical application of new green technologies in expressway service areas should be strengthened.

Keywords

Expressway service area; Reclaimed water; Wastewater treatment; Reuse technology; Carbon emission.

1. Introduction

With the rapid development of the economy and the increase in population in our country, water resource scarcity has become a key focus in current water environment research. As a novel water-saving method, reclaimed water has become an important water source considered by governments worldwide. In countries such as the United States, Japan, Germany, and Israel, reclaimed water is widely applied, often used for flushing toilets, landscaping and agricultural irrigation, road cleaning, car washing, urban fountains, and supplemental cooling water for equipment [1].

The application of reclaimed water in one area, namely highway service areas, is still not widespread. This is particularly true because most service areas are located far from urban areas, requiring a significant investment to connect to sewage networks. As a result, in most cases, wastewater generated is either discharged after treatment by small independent sewage facilities or is reused. By the end of 2023, the total length of highways in China had reached 177,300 kilometers, and the annual passenger traffic on these roads had exceeded 3.5 billion people[5]. The daily water consumption at service areas is substantial; if discharged untreated, it can easily contaminate water sources along the highways, leading to serious ecological and social issues[6].With the issuance of the "Water Pollution Prevention and Control Action Plan" by the State Council, it has been proposed that service areas strengthen water conservation efforts and that sewage treatment must shift from meeting discharge standards to achieving regeneration and reuse[7]. Thus, the application of reclaimed water systems in highway service areas and the improvement of reclaimed water reuse technology has become an increasingly important and hot issue.

2. Characteristics of Wastewater in Service Areas

The main water uses in highway service areas include toilet flushing in public restrooms, washing water for staff and visitors, water for food and beverage services, as well as water for cleaning the service area, green space irrigation, and road sprinkling. Except for washing and food and beverage services, which have strict water quality standards and must use domestic water, the rest can utilize reclaimed water that meets reuse standards after treatment. According to existing survey results[8,9], toilet flushing wastewater in public restrooms can account for 40-80% of the total wastewater in service areas, domestic wastewater from washing, bathing, etc., of staff and visitors accounts for 10-30%, food and beverage wastewater accounts for 10-30%, and other wastewater such as car washing accounts for 5-10%.

2.1. High pollution load

A summary of monitoring results for typical service area wastewater across various regions in the country is provided, with representative data shown in Table 1. The actual COD (Chemical Oxygen Demand) in highway service area wastewater can reach up to 700 mg/L, and ammonia nitrogen can reach 200 mg/L. Compared to urban domestic wastewater, it has a higher organic pollutant index, higher concentrations of suspended solids, nitrogen, and phosphorus. Moreover, there are significant differences in pollutant indices among different regions, influenced by the supporting infrastructure of each service area. Therefore, different service areas should select appropriate wastewater treatment systems and reclaimed water reuse technologies based on their actual pollution load conditions.

Table 1. Typical influent water quality of wastewater in service areas

Service Area	COD (mg/L)	BOD5 (mg/L)	SS (mg/L)	NH3-N (mg/L)	Total P (mg/L)	pH
Baoji[8]	252	113	89	45.8	4.22	7.95
Luochuan	435	196	122	79.7	7.32	8.24
Jiangsu[10]	514	269	-	162	12.6	-
Jinzhong[11]	445	151	64	69	8.9	7.81
Southern Shanxi	321	112	95	91	5.6	7.19
Northern Shanxi	486	164	81	76	5.8	7.31
Nanchang[12]	700	-	-	200	15	7.8
Yunnan	-	138	329	211	15.1	-

2.2. Large water volume fluctuations

According to survey findings, the wastewater volume in highway service areas is significantly influenced by passenger and vehicle traffic, resulting in unstable water volumes with large daily and quarterly fluctuations. Additionally, the wastewater volume in summer is notably higher than that in winter[14,15]. The daily average wastewater volume in most service areas ranges from 30 to 200 m^3, with a few exceptions exceeding 200 m^3. Service areas are susceptible to peak impacts during weekends and holidays, where the water volume can reach 2 to 5 times the usual level, demonstrating significant fluctuations. Furthermore, there is a trend of initial low passenger traffic during the early stages of highway operation, followed by an annual increase. Due to the strong correlation between wastewater discharge and passenger traffic, the wastewater volume also increases annually[16].

3. Analysis of Reclaimed Water Reuse Technology in Service Areas

Traditional reclaimed water reuse technologies in highway service areas commonly employ methods such as activated sludge, contact oxidation, and biological membrane processes. As China's water scarcity issues intensify and standards for wastewater treatment and reuse elevate, numerous new water treatment technologies have been applied in service areas in recent years, including photocatalytic oxidation technology[17,18], membrane separation technology, biological flocculation technology, and ultrasonic technology[19,20]. The optimization and combination of traditional treatment processes also represent a major trend in reclaimed water reuse in service areas.

3.1. Activated Sludge Process

The Activated Sludge Process (ASP) is one of the earliest technologies applied, known for its high efficiency in removing organic matter and suspended solids. The basic flowchart is shown in Figure 1. Currently, common treatment processes include the Sequencing Batch Reactor (SBR) method, the AB process, the oxidation ditch method, and the step-feed activated sludge process, among others.

The Sequencing Batch Reactor (SBR) method, also known as the intermittent activated sludge process, was developed by Professor Irvine in the United States in the 1970s [21,22]. This process is relatively simple, occupies a small footprint, and has low construction and operational costs. It is also effective in removing organic pollutants, nitrogen, and phosphorus from wastewater. The greatest advantage of this process is that the aeration and sedimentation stages of wastewater treatment are carried out sequentially in a single tank. Depending on the variation in influent volume, the duration of each stage can be adjusted[23,24]. This process has a strong resistance to shock loads and can effectively address the issue of large fluctuations in wastewater volume in service areas.

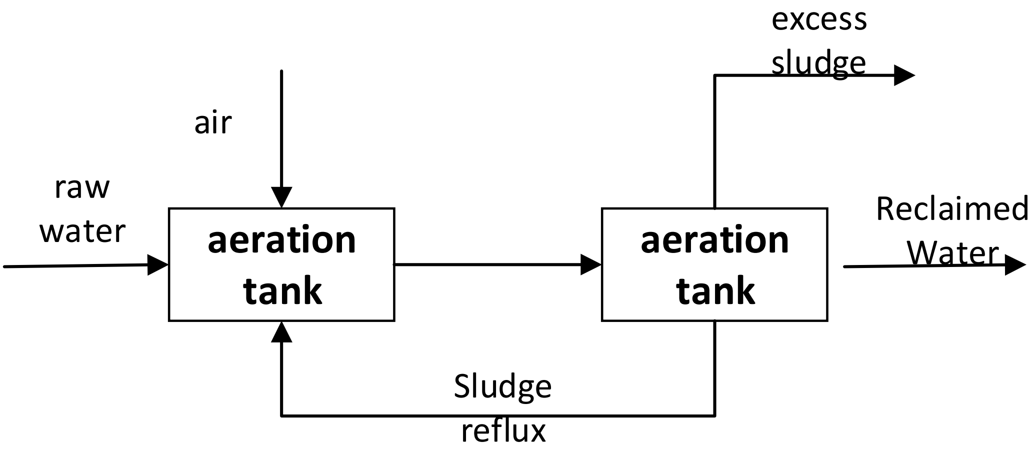

Figure 1. Activated sludge process

The AB process (Adsorption-Biodegradation process)[25,26] is a new type of activated sludge process that consists of two stages, A and B, with high and low sludge loads, respectively, and each stage has its own independent sludge return system. The AB process is effective in treating high-concentration domestic wastewater and produces stable effluent. However, it generates a high amount of sludge that needs to be transported and disposed of promptly, making it unsuitable for service area buildings located in remote areas.

3.2. Biofilm Process

The Biofilm Process utilizes microbial communities attached to the surface of solid media to form a biofilm for treating wastewater. Similar to the Activated Sludge Process, it relies on microorganisms to remove organic matter from wastewater.

The Membrane Bioreactor (MBR) method is a wastewater reuse treatment technology that combines membrane separation technology with the Activated Sludge Process. It leverages the selective permeability of membranes to different pollutants and retains microorganisms to achieve efficient degradation of pollutants, as depicted in Figure 2. Compared to traditional sludge methods, the MBR method can maintain a higher biomass with less sludge production[27]. Moreover, it provides stable effluent quality and excellent treatment results, achieving advanced treatment standards, and can be directly reused after disinfection[28]. As a relatively mature technology in reclaimed water reuse, it has been widely applied in highway service area buildings. However, a drawback is its high operation and maintenance costs, making it suitable for service areas with relatively high operation and maintenance standards.

Based on the specific characteristics of different service areas, the MBR method is continuously being optimized and improved. Li Guoxiong[29] found through research that the MBR system in highway service areasexperiences a gradual decrease in denitrification function during long-term operation. To address this, a biological enhancement process was designed to strengthen reclaimed water treatment and ensure more sustained and stable operation of the MBR system. Yin Lei et al.[30] retrofitted the existing wastewater treatment facilities in a service area with a combined " MBBR+MBR" reclaimed water reuse system, which has high promotional value for the renovation of older service areas. Xin et al.[31] studied the "MBBR+A/O" process for treating service area wastewater and found that, compared to traditional processes, it achieved a 15.24% higher Total Nitrogen (TN) removal rate and 121.9% higher denitrification rate.

3.3. Contact Oxidation Process

The Contact Oxidation Process, as a more advanced technology in wastewater treatment, includes the hydrolytic acidification-contact oxidation process, anaerobic-aerobic oxidation process (A/O), and anaerobic-anoxic-aerobic process (A2/O). It is commonly applied in buried integrated equipment in highway service areas. Li et al. [9] conducted a survey of highway service areas across the country and found that 82.3% of the service areas use buried integrated wastewater treatment equipment, with the three processes accounting for approximately 85%, 10%, and 5%, respectively.

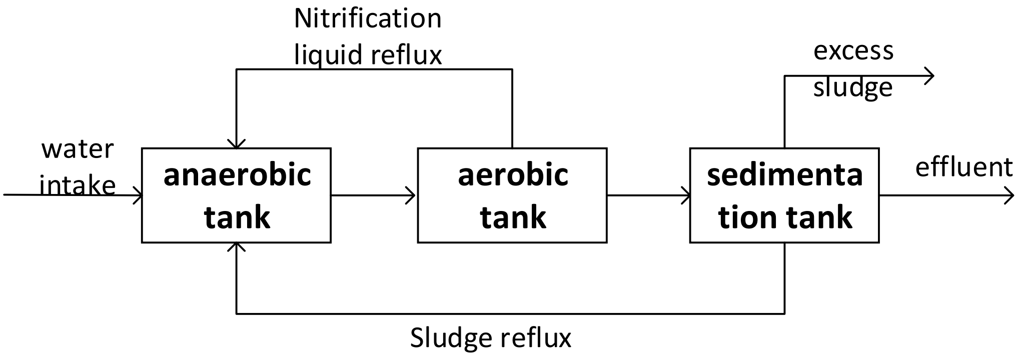

Figure 2. A/O Process Flow Chart

The A/O process is a fundamental technology in biological wastewater treatment, but its treatment capacity is limited, and the operational costs significantly increase when dealing with high pollution loads. Therefore, highway service areas often combine the A/O process with reuse technologies, primarily MBR. Hu Fengping et al. [32] adopted the A/O + MBR process based on the wastewater characteristics of a highway service area in Jiangxi. The operational results showed that the effluent quality could meet the reuse requirements outlined in the "Standard for Reuse of Urban Wastewater - Water Quality Standard for Urban Non-Potable Use." Zhang Yuanguo [33] upgraded the wastewater treatment process in a service area from the original A/O + quartz sand filter to the A/O + MBR process, resulting in stable effluent quality that exceeded the Class 1A standards of the "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants." Deng Lizhi [12] studied the treatment of service area wastewater using the "artificial zeolite + coagulation + A/O" process, achieving removal rates of 93.1%, 34.8%, 91.6%, and 20.8% for ammonia nitrogen, COD, TN, and TP, respectively. This significantly improved the carbon-to-nitrogen ratio of the wastewater, which is more favorable for subsequent reclaimed water reuse.

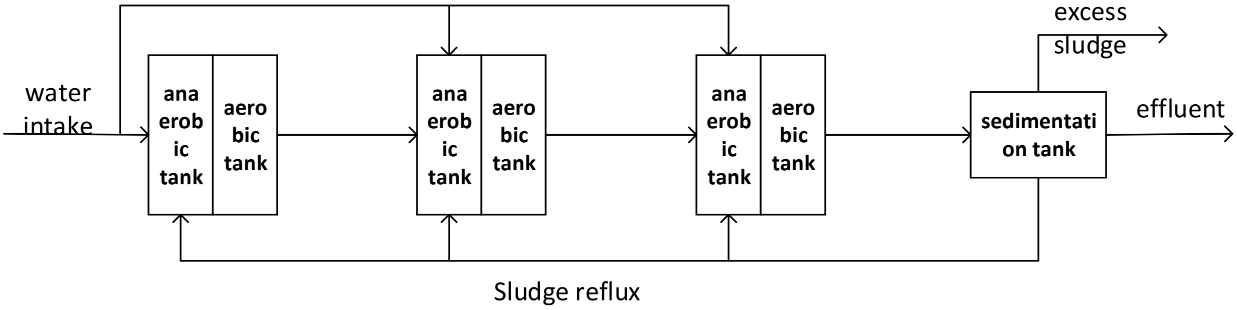

Figure 3. Multi level A/O process flowchart

In recent years, the reverse A/O process has also been applied in some service areas. However, due to the complex daily operation procedures and high failure rates of the equipment, it has failed to achieve its designed effects and environmental benefits, making it impractical for further promotion.

Currently, the integrated equipment for wastewater treatment in service areas mostly adopts the multi-stage A/O process, which is an improved process based on the A/O process. It connects multiple sets of anaerobic/aerobic tanks, where reactions alternate to enhance treatment effectiveness. The segmented inflow of wastewater into each anaerobic stage can effectively reduce the impact of pH and dissolved oxygen from the previous stage's effluent. In practical engineering, due to factors such as land area and capital investment, the multi-stage A/O process generally does not exceed four stages [34]. The multi-stage A/O process exhibits strong resistance to shock loads, high nitrogen and phosphorus removal rates, and stable operation, making it suitable for wastewater treatment in highway service areas.

3.4. Ecological treatment technology

The main ecological treatment technologies include soil treatment, multi-biological filtration, and constructed wetlands, among which constructed wetlands are the most common ecological treatment technology used in highway service areas.

A constructed wetland is an ecological wastewater treatment system that mimics the structure and function of natural wetlands. It artificially regulates the integration of soil, microorganisms, and plants into an ecosystem. After pretreatment, wastewater is conveyed to the land with artificial aquatic and wetland plants, where it is purified through the interception and sedimentation by water-tolerant plants and natural degradation by soil, providing a guarantee for the reuse of reclaimed water in service areas. This technology achieves an effective combination of wastewater treatment and ecological governance, as well as the resource utilization of wastewater, with the advantages of low cost and simple management [36]. However, it also has disadvantages such as a large land footprint, and the plants and microorganisms in constructed wetlands are affected by regional and climatic factors, making it difficult to maintain stable effluent quality over the long term. Therefore, it is not suitable for highway service areas in cold regions. Lin Dandan et al. [37] proposed that, in terms of the application effect of horizontal subsurface flow wetlands in service areas, measures should be taken according to local conditions, selecting native emergent plants and considering a combination of multiple plant species for planting.

4. Current Issues

(1) The design objective does not match the actual sewage conditions. In the actual operation of highway service areas, the peak operation time of the sewage system accounts for only 8.2% of the annual operation time, with most of the time spent in low-load operation. The actual sewage volume in various service areas is only 20%-40% of the designed treatment capacity. Excessive treatment equipment volume can lead to prolonged sewage retention time, resulting in unstable effluent quality that fails to meet standards, low reuse efficiency, and significant energy wastage.

(2) Low level of operation and maintenance. Due to the widespread lack of professional management personnel for sewage systems in highway service areas, maintenance efforts vary greatly. Moreover, constrained by factors such as geographical location, staffing, and maintenance funds, daily debugging, repairs, and equipment part replacements for reclaimed water systems face certain difficulties, leading to the long-term shutdown or abnormal operation of reclaimed water systems in some service areas.

(3) Insufficient research on sewage reuse in highway service areas. In China, past research often focused on achieving discharge standards after treatment, while research on sewage reuse started relatively late, with insufficient literature. Most studies remain at the theoretical analysis stage and lack practical application research in service areas.

5. Conclusion

The sewage treatment facilities in service areas are crucial auxiliary facilities for water pollution prevention and control during highway operation. The treatment process should be selected reasonably by combining the characteristics of sewage in service areas, geographical and climatic factors, and adopting complementary combined treatment processes.

Research conducted so far indicates that the activated sludge process, as a traditional sewage treatment technology, can no longer meet the current demands for sewage treatment in service areas. Advanced technologies are required to handle high loads of sewage, while also addressing the high sludge production associated with this method.

MBR method is relatively mature and has strong pollutant treatment capabilities, significantly outperforming the traditional activated sludge process. However, it requires enhanced daily maintenance to ensure its long-term stable operation in service areas.

Although constructed wetlands are mostly used for treating domestic sewage, they are highly suitable for sewage treatment in highway service areas after improving their pretreatment processes. Considering their low cost, ease of management, and certain landscape effects, they may be more suitable for widespread adoption.

References

[1] Wu Haohao, Xiao Zhiyi. Development and Application of Reclaimed Water Reuse Technology [J]. Journal of Green Science and Technology, 2023, 25(02): 202-208.

[2] Li Yong, Liu Jing, Wang Wenpeng. Discussion on the Current Status and Existing Problems of Reclaimed Water Reuse Technology [J]. Journal of Green Science and Technology, 2018, 2(2): 49-50.

[3] Li Wei. Research on Technology and Issues of Urban Reclaimed Water Reuse [J]. Jiangxi Building Materials, 2022(1): 219-221.

[4] Li Mingxing. Analysis of the Application of Reclaimed Water Reuse Technology in Construction Projects [J]. Henan Building Materials, 2019, 14(1): 246-247.

[5] National Bureau of Statistics. China Statistical Yearbook [R]. Beijing: China Statistics Press, 2023.

[6] Ding Bo. Research on Emergency Capability Assessment Methods for Sudden Events in Expressway Service Areas [D]. Changchun: Jilin University, 2015.

[7] State Council. Action Plan for Water Pollution Prevention and Control [Z]. Beijing: State Council, 2015.

[8] Liao Jianan. Analysis and Countermeasures of Sewage Treatment Status in Shaanxi Expressway Service Areas [D]. Chang'an University, 2019.

[9] Jian Li, Jialin Yao, Xuexin Liu, et al. Evaluation and Analysis of Wastewater Treatment Technology Applied in Highway Service Area [J]. IOP Conference Series: Earth and Environmental Science, 2020, 474: 072097.

[10] Liang Liping, Zhang Lin. Current Status and Countermeasures of Sewage Treatment in Jiangsu Expressway Service Areas [J]. China Water & Wastewater, 2017, 33(04): 20-25.

[11] Zhao Yue. Study on the Applicability of Sewage Treatment Processes in Shanxi Expressway Service Areas [J]. Shanxi Transportation Science and Technology, 2023, (06): 100-102+120.

[12] Deng Lizhi. Research on Treatment and Optimization of Low C/N Ratio Sewage in Expressway Service Areas Based on Synthetic Zeolite [D]. Nanchang University, 2024.

[13] Gao Yang, Qing Xiaoyan, Jiang Wenjiang, et al. Intelligent Sewage Treatment Technology and Its Application in Yunnan Expressway Service Areas [J]. Journal of Transportation Energy Saving and Environmental Protection, 2021, 17(06): 111-114.

[14] Hu Jing. Characteristics and Treatment Processes of Sewage in Expressway Service Areas [J]. Jiangsu Science & Technology Information, 2018(10): 61-63.

[15] Zhang Shui, Huang Jiayuan, Zhang Ruixue, et al. Characteristics and Treatment Process Selection of Sewage Discharge in Guizhou Expressway Service Areas [J]. Water & Wastewater Engineering, 2017, 53(S1): 120-122.

[16] Lin Qi. Research on Sewage Characteristics in Expressway Service Areas [J]. Energy and Environment, 2013(1): 12-14.

[17] Li Jiao. Experimental and Simulation Methods for Photocatalytic Oxidation of Wastewater Treatment Systems Using TiO2 with Different Morphologies [D]. South China University of Technology, 2022.

[18] Cheng Haitao. Research on the Degradation of Sewage in Expressway Station Areas Using TiO2/Activated Carbon Composites [D]. Shanxi University, 2022.

[19] Ren Liye. Research on Low-Intensity Ultrasound Promoting Short-Nitrification of Sewage [D]. Jiangxi University of Science and Technology, 2020.

[20] Tian Shuai. Research on the Mechanism of Low-Intensity Ultrasound Enhancing Anaerobic Biological Treatment of Sewage [D]. Jiangxi University of Science and Technology, 2021.

[21] Singh M, Srivastava K R. Sequencing Batch Reactor Technology for Biological Wastewater Treatment: A Review [J]. Asia-Pacific Journal of Chemical Engineering, 2011, 6(1): 3-13.

[22] Benavides JS, Marianna V, Davide D. Model-Based Comparison of Sequencing Batch Reactors and Continuous-Flow Activated Sludge Processes for Biological Wastewater Treatment [J]. Computers and Chemical Engineering, 2021, 144.

[23] Li Hantong. Discussion on Urban Sewage Treatment Technology [J]. Building Materials & Decoration, 2016(10): 152-153.

[24] Xie Fenglian, Xu Lezhong, Wu Peng. Treatment of Volatile Organic Compound-Containing Wastewater by Adsorption-Biodegradation [J]. Applied Chemical Industry, 2021, 50(01): 39-44.

[25] O.T. Iorhemen, R.A. Hamza, J.H. Tay, Membrane Bioreactor (MBR) Technology for Wastewater Treatment and Reclamation: Membrane Fouling, Membranes, 6(2) (2016), p. 33, 10.3390/membranes6020033.

[26] Long Bo. Current Status and Development Trends of New Sewage Treatment Technologies [J]. Resource Information and Engineering, 2018, 33(2): 179-180.

[27] Li Guoxu. Research on Biological Enhanced MBR Process for Treating Wastewater in Expressway Service Areas [D]. Chongqing University of Technology, 2023.

[28] Yin Lei, Guo Jiantao, Xu Guozhu, et al. Application of Intelligent "MBBR+MBR" in Reclaimed Water Reuse in Expressway Service Areas [J]. Value Engineering, 2023, 42(18): 111-114.