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A practical study on the near-zero discharge of rainwater and the collaborative treatment and regeneration of rainwater and sewage

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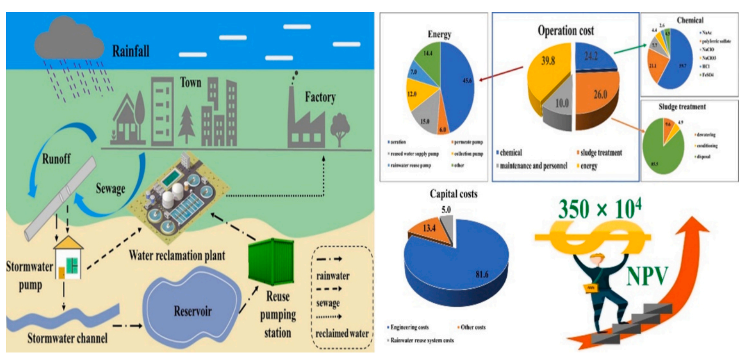
HIGHLIGHTS

- An efficient and profitable technology for wastewater regeneration
- The reclaimed water becomes a sustainable and profitable source of industrial water.
- Comprehensive collection, storage and distribution of rainwater across time and space
- A comprehensive cost-benefit analysis indicates a positive NPV for the WRP.

GRAPHICAL ABSTRACT



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ABSTRACT

Non-conventional water recovery, recycling, and reuse have been considered imperative approaches to addressing water scarcity in China. The objective of this study was to evaluate the technical and economic feasibility of Water Reclamation Plants (WRP) based on an anaerobic-anoxic-oxic membrane bioreactor (A^2O-MBR) system for unconventional water resource treatment and reuse in towns (domestic sewage and rainwater). Rainwater is collected and stored in the rainwater reservoir through the rainwater pipe network, and then transported to the WRP for treatment and reuse through the rainwater reuse pumping station during the peak water demand period. During a year of operation and evaluation process, a total of 610,000 cubic meters of rainwater were reused, accounting for 10.4 % of the treated wastewater. In the A^2O-MBR operation, the average effluent concentrations for COD (chemical oxygen demand), NH_4^+-N (ammonium), TN (total nitrogen), and TP (total phosphorus) were 14.23 ± 4.07 mg/L, 0.22 ± 0.26 mg/L, 11.97 ± 1.54 mg/L, and 0.13 ± 0.09 mg/L, respectively. The effluent quality met standards suitable for reuse in industrial cooling water or for direct discharge. The WRP demonstrates a positive financial outlook, with total capital and operating costs totaling 0.16 $/m^3. A comprehensive cost-benefit analysis indicates a positive net present value for the WRP, and the

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estimated annualized net profit is 0.024 $/m^3$. This research has achieved near-zero discharge of wastewater and effective allocation of rainwater resources across time and space.

1. Introduction

Around 80 % of the global population is facing substantial water security challenges, a predicament heightened by escalating water scarcity resulting from climate change, population growth, and economic development (Bakker, 2012; Koop et al., 2022; Mihelcic et al., 2017). To tackle this issue, a crucial shift toward more sustainable water use is imperative (Prouty et al., 2018). This entails embracing development practices that can be sustained indefinitely, concurrently alleviating adverse social, economic, and environmental impacts. One promising solution is the utilization of Unconventional Water Resources (UWRs) as an alternative water source to overcome water scarcity (Baggio et al., 2021; Karimidastenaei et al., 2022). In 2020, the European Commission (EC) established a legal requirement for water reuse in agriculture across the European Union (EU). EU Regulation (2020/741) outlines minimum standards for water reuse, prompting member states to adopt strategies for reclaimed water utilization (Cosenza et al., 2023). China's per capita water resources are only about one-fourth of the world average. In response to the water crisis, a series of policies has been promulgated, including "The Yellow River Protection Law" and the "Water Pollution Prevention and Control Law of the People's Republic of China," which emphasize the importance of increased wastewater treatment and reuse as crucial measures to address these concurrent crises (Lyu et al., 2016; Qu et al., 2022). Firstly, municipal wastewater reuse holds the potential to significantly augment the overall water resources of the country. Secondly, rainwater, acknowledged as a clean and sustainable resource, has emerged as a crucial avenue for development (Frieberg et al., 2023; Zanni et al., 2019). The practices of rainwater harvesting and reuse not only offer solutions to various challenges, such as alleviating the water crisis and relieving pressure on traditional water sources but also yield additional benefits (Sweetapple et al., 2023; Zhou et al., 2021). These advantages encompass the reduction of non-point source pollutant loads, resolution of waterlogging issues, prevention of flooding, and contribution to climate change mitigation (Soh et al., 2023).

Therefore, a range of sewage treatment approaches, encompassing chemical, physical, and biological methods, are applied for the treatment of municipal sewage and stormwater (Morris et al., 2017). These methods include constructed wetlands (Wu et al., 2018), solid filtration beds (Huang et al., 2023), traditional activated sludge processes (Tang et al., 2016), submerged membrane bioreactors (SMBR) (Sano et al., 2020), and various membrane treatment systems (Qin et al., 2018). Many membrane-based systems for treating wastewater and producing high-quality treated water have been thoroughly studied (Garrido-Baserba et al., 2022). Membrane-based systems have many advantages over conventional wastewater treatment technologies (Lan et al., 2018). Membranes act as permanent barriers, effectively blocking suspended particles, including bacteria and viruses, as well as macromolecules larger than the pore size of the membrane material (Men et al., 2023). This mechanism significantly enhances the quality of the treated wastewater. The compact nature of membrane systems minimizes their environmental impact, aligning well with the principles of sustainable development (Yan et al., 2018). Nowadays, MBR has been widely accepted and applied as an efficient wastewater treatment process in China, due to its clean effluent and rapid performance improvement in many aspects, such as membrane lifespan, fouling mitigation, and energy consumption reduction (Lee et al., 2018; Monclús et al., 2015). Furthermore, the reduction in membrane prices and advancements in membrane materials have further propelled the efficiency of membrane systems in treating wastewater, particularly where economically feasible (Liu et al., 2022).

This study delves into the comprehensive process of collecting, treating, and reusing municipal sewage and rainwater in Dalat Banner, a semiarid and water-scarce region in China. The rainwater and sewage collection area covers the entire urban area of Dalat Banner, covering an area of about 30.7 km^2. Rainwater collected during the rainy season is temporarily stored in rain reservoirs. In contrast, during the peak water demand period, the accumulated rainwater in the storage pond is conveyed to a reclaimed water plant through dedicated rainwater reuse facilities for treatment and subsequent disposal. The heart of this process lies in the utilization of the A^2O-MBR process at the reclaimed water plant. This advanced treatment method facilitates collaborative efforts in treating both rainwater and pollutants, ensuring that the effluent meets high-quality standards. The treated reclaimed water is transported to industrial parks, where it becomes a sustainable and profitable source of industrial water. This integrated approach not only addresses the collaborative treatment and management of urban sewage and stormwater but also emphasizes the importance of recycling.

2. Materials and methods

2.1. Wastewater treatment system

Situated in northern China, this treatment plant efficiently processes large volumes of domestic sewage and stormwater from cities and towns, handling up to 20,000 cubic meters per day (Fig. 1). Notably, all treated water is reused as industrial water. The preliminary treatment includes coarse screens, fine screens, an aerated grit chamber, and an ultra-fine screen, successively removing the majority of suspended solids. Following this preliminary treatment, the wastewater undergoes the A^2O-MBR system for further processing. This system plays a pivotal role in finalizing the removal of COD, nitrogen, and phosphorus nutrients. Specifically, within the A^2O-MBR system, there are 36 sets of membrane modules, each composed of hydrophilic PVDF with a pore size of 0.3 μm. Remarkably, each set demonstrates a water production capacity of 834 m^3/d. After the A^2O-MBR process, the wastewater is directed to a magnetic coagulation system for further phosphorus removal. Subsequently, it undergoes disinfection with chlorine dioxide before being stored in a clean water tank for the subsequent reuse phase. This comprehensive treatment process showcases an efficient and advanced approach to managing wastewater, ensuring high-quality industrial water recycling in the region.

2.2. Harvesting system and reused system

As illustrated in Fig. 2, the primary sources contributing to wastewater include domestic sewage and rainwater. Domestic sewage originates from the day-to-day activities of urban residents, involving tasks such as washing, cooking, flushing toilets, and other water-related activities. During the rainy season, the municipal pipe network collects rainwater, directing it through the rainwater pumping station to discharge into the downstream rainwater reservoir. During the peak water demand period, the rainwater reuse pump station becomes operational, facilitating the conveyance of rainwater to the WRP.

2.3. Sampling and analytical methods

The WRP employs real-time monitoring facilitated by in-line sensors to systematically track and gather data on incoming and outgoing water flow, temperature, pH, and dissolved oxygen (DO). Following the standard water and wastewater inspection method (APHA, 2012), a thorough analysis of various key parameters in both influent and effluent is conducted. Samples were collected at the front end of the coarse screen and in the clear water tank. These parameters encompass COD (Chemical Oxygen Demand), TN (Total Nitrogen), NH_4^+-N (Ammonium Nitrogen), NO_3^--N (Nitrate Nitrogen), TP (Total Suspended Solids), VSS (Volatile Suspended Solids), turbidity, and other pertinent indicators. This meticulous analysis serves the dual purpose of ensuring compliance with established water quality standards and offering valuable insights into the efficacy of the treatment process. The real-time monitoring system, coupled with comprehensive parameter analysis, reinforces the unit's commitment to maintaining high water quality standards and continuously improving its wastewater treatment practices. Fecal *E. coli* and heavy metal indicators are monitored monthly, with the analysis method and equipment details provided in Table S3 of the supplementary material.

2.4. Cost-benefit analysis modeling

To assess the economic viability of wastewater reuse projects, traditional economic analysis methods, such as Cost-Benefit Analysis (CBA) are essential. CBA serves as a widely used index for evaluating the economic aspects of wastewater treatment (Arroyo and Molinos-Senante, 2018; Finnerty et al., 2023). It involves comparing revenue against costs, where revenue is derived from the sale of recycled water and other secondary products. Costs encompass various elements, including capital expenditures, operational and maintenance expenses, and financial outlays. Capital costs include expenses like land acquisitions, pipe and pump installations, well construction, and procurement of equipment and materials. Operational and maintenance costs cover energy costs for pumping, pipeline upkeep, labor, chemicals, administrative expenses, additional processing energy, repairs, and material consumption.

2.4.1. Capital costs (Cap)

Since the construction cost of the rainwater and sewage collection municipal website and the rainwater reservoir is government infrastructure, it is not included in the cost consideration. Therefore, the capital cost of this project only considers the capital investment of various infrastructures at the time of the initial construction of the raw water plant. It mainly includes engineering costs, other costs, and rainwater reuse system costs. The main considerations for calculating the capital costs are outlined in Eq. (1) and Table 1.

$$C_{ap} = C_{ape} + C_{apo} + C_{apr} \tag{1}$$

Engineering costs (C_{ape}): The engineering costs include the sewage pretreatment system, sludge treatment system, aeration system, disinfection system, reclaimed water supply system, A^2O-MBR system, and dosing system.

Other costs (C_{apo}): Construction land cost, engineering survey cost, engineering design cost, etc., are the main components of other costs.

Rainwater reuse system costs (C_{apr}): The cost of a rainwater reuse system mainly includes a stormwater reuse pumping station, rainwater reuse pipeline, and other expenses.

2.4.2. Operational costs (O_{pc})

The operating costs of the reclaimed water plant include the sum of energy consumption, chemical expenses, sludge treatment, equipment maintenance, and staff costs.

$$O_{pc} = O_{pce} + O_{pcc} + O_{pcs} + O_{pcm} + O_{pcp} \tag{2}$$

Energy consumption (O_{pce}): It mainly involves the use of electricity in recycled water plants, sewage collection pumps, flow pushers, aeration equipment, MBR backwashing, MBR feed pumps, disinfection systems, rainwater reuse pumps, and reused water supply pumps.

Chemical expenses (O_{pcc}): The expenses for chemical reagents encompass various components, such as chemicals used for cleaning membranes (NaClO) and disinfection systems ($NaClO_3$ and HCl). Carbon source sodium acetate, phosphorus removal agent polyferric sulfate.

Sludge treatment (O_{pcs}): The plate and frame filter dehydrator is chosen for sludge dewatering requiring polyacrylamide (PAM) for proper sludge conditioning. The dehydrated sludge (moisture content below 80 %) is directly handed over to the company with sludge treatment qualification for treatment and disposal.

Maintenance (O_{pcm}) and personnel (O_{pcp}) costs: The equipment lifetime is determined according to recommendations provided by the manufacturer.

2.4.3. Net profit

The net present value (NPV) is calculated as the sum of the capital costs, operating costs, and incomes generated by the WRP (Djukic et al., 2016; Estrada et al., 2012; Wang et al., 2019). The method described in the following equation is based on a whole plant operation period of 20 years. The lifespans of the main capital components are listed in Table 1, with a long-term 6 % nominal interest rate and 3 % inflation rate used in this study (Ferrer et al., 2015).

$$NPV = \sum_{t=0}^{19} \left(\frac{(Inc)_t - (O_{pc})_t - (C_{ap})_t}{(1+i)^t} \right) \tag{3}$$

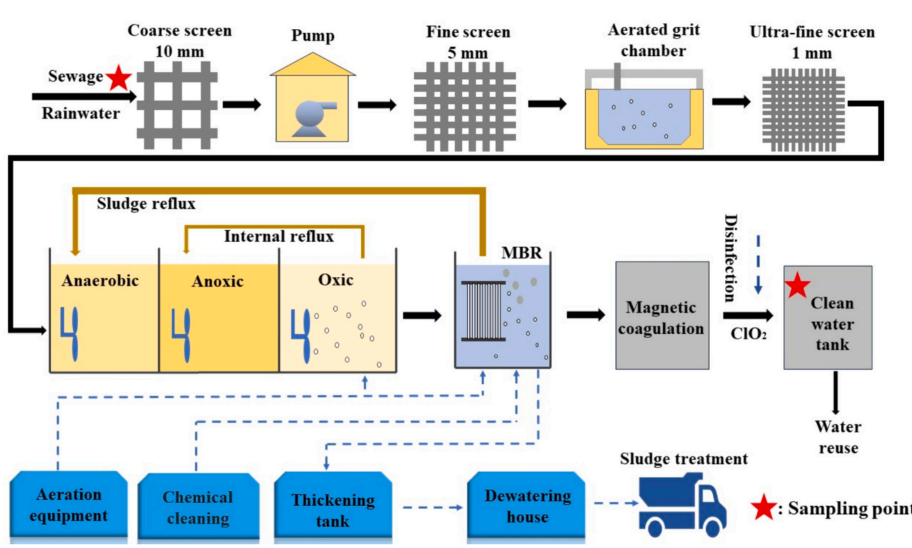

Fig. 1. The process flow of the WRP.

In the formula, NPV represents the net profit value, *Inc* stands for the income value, O_{pc}represents the annual operation cost, and C_{ap} is the cost value. The nominal interest rate is denoted by i. For a specific project, it is deemed economically feasible when the NPV $>$ 0. Conversely, if the NPV $<$ 0, the project is considered economically unviable. Recycled water as industrial cooling water is sold to enterprises for profit, and the income is *Inc*.

3. Results and discussion

3.1. Rainwater collection and reuse

This study is situated in Dalat Banner, Ordos City, China, an area characterized by a temperate continental climate with strong winds, sandy, and dry conditions, and limited rainfall. Summers are hot and short, while winters are cold and long (Fig. 3a), resulting in noticeable temperature variations between seasons. Fig. 3b illustrates that the average annual rainfall in Dalat Banner is 327.0 mm, with precipitation concentrated from July to September, accounting for 71 % of the annual total. In this project, rainwater will be collected through the stormwater pipe (Fig. 2) into the rainwater reservoir (Fig. 4c) for treatment and reuse, covering an approximate catchment area of 30.7 km^2. With a runoff coefficient of 0.3, the annual rainwater collected amounts to about 3×10^6 m^3. To maintain optimal storage and drainage capacity in the existing rainwater reservoir, ensure good water quality, and protect the aquatic ecological environment, anti-seepage works have been carried out. The reservoir (Fig. 4c) area spans about 145,000 m^2, with a reservoir depth of approximately 6 m, resulting in a rainwater storage capacity of about 900,000 m^3. Since the operation of the rainwater recovery pump house from March 28, 2023, to December 28, 2023, it has been operational for 195 days, with a cumulative recovery of 601,900 tons of rainwater and an average daily recovery of 3086.6 m^3 of rainwater (Fig. 5). Rainwater treatment water accounts for about 10.4 % of the total water treated by the WRP.

3.2. Water treatment performance

3.2.1. Organic removal

All kinds of complex organic matter in wastewater are primarily degraded by activated sludge microorganisms in the aerobic tank. The MBR efficiently intercepts almost all bacteria and suspended matter in the wastewater, facilitating the growth and reproduction of nitrifying bacteria and other slowly proliferating bacteria. This, in turn, improves the system's COD removal rate and other key indicators, significantly shortening the reaction time (Li et al., 2009; Li et al., 2019; Lu et al., 2019). The examination of the operation of the WRP, spanning from January 1, 2023, to November 30, 2023. Initially, focusing on the removal performance of organic matter, Fig. 6b and Table 1 illustrate the influent and effluent COD concentrations of the WRP, along with the removal rates during operation. The COD influent concentration peaked at 1321 mg/L before May. This high concentration is attributed to the low temperatures during the winter season, which result in reduced mildly polluted domestic wastewater (from activities like bathing and washing water). Additionally, only a relatively small amount of rainwater entered the WRP until March 28th. However, the COD concentration of the effluent remained below 20 mg/L, indicating that the WRP has the ability to cope with stronger changes in water quality. Following this, the COD concentration of the influent water gradually decreased, reaching 315.17 ± 3.51 mg/L. This reduction coincided with warming weather, resulting in increased water usage for washing by residents. Simultaneously, the onset of the season introduced a significant amount of rainwater into the WRP. Rainwater, being a lightly polluted water source, exerted a dilution effect on domestic sewage.

Table 1
The removal performance of contaminants in WRP.

Index	Influent quality (mg/L)	Effluent quality (mg/L)	Removal efficiency (%)
COD	524.10 ± 274.37	14.22 ± 4.06	96.68 ± 1.55
NH_4^+-N	39.81 ± 13.58	0.22 ± 0.26	99.38 ± 0.56
TP	4.03 ± 0.52	0.13 ± 0.09	96.65 ± 2.63
SS	176.16 ± 14.17	8.03 ± 0.84	95.40 ± 0.89

3.2.2. Nitrogen removal

Nitrogen removal in the A^2O process primarily involves biological nitrification and denitrification. In this process, the mixed liquid from the end of the aerobic zone and the sewage from the anaerobic zone enter the anoxic zone together for denitrification. Biological denitrification is a process in which nitrate nitrogen (NO_3^--N) and nitrite

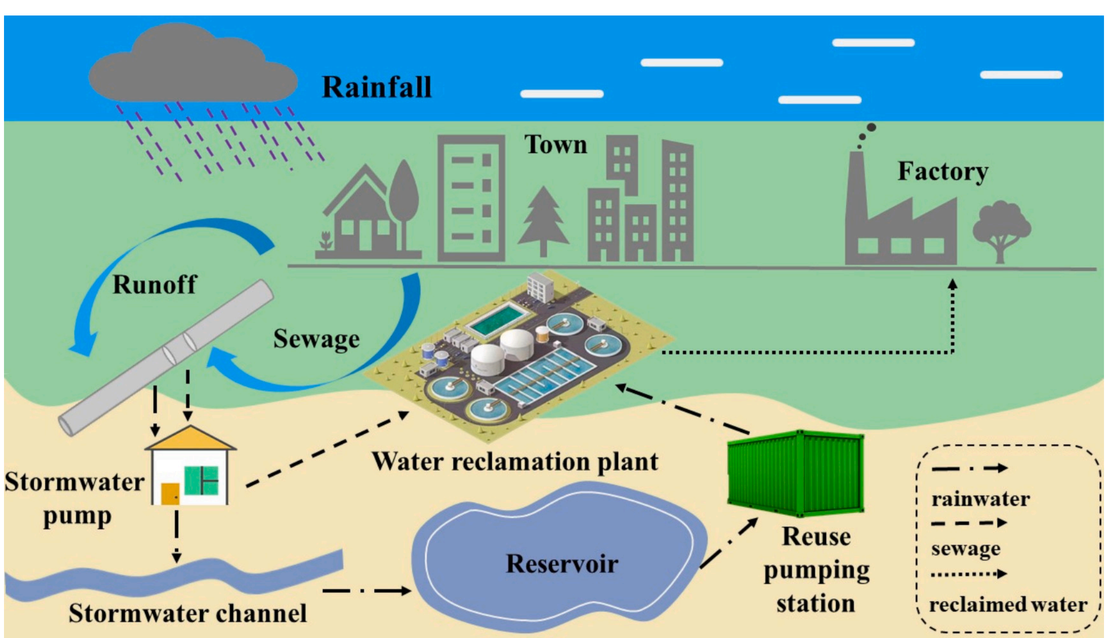

Fig. 2. The process of collecting, treating, and reusing rainwater and sewage.

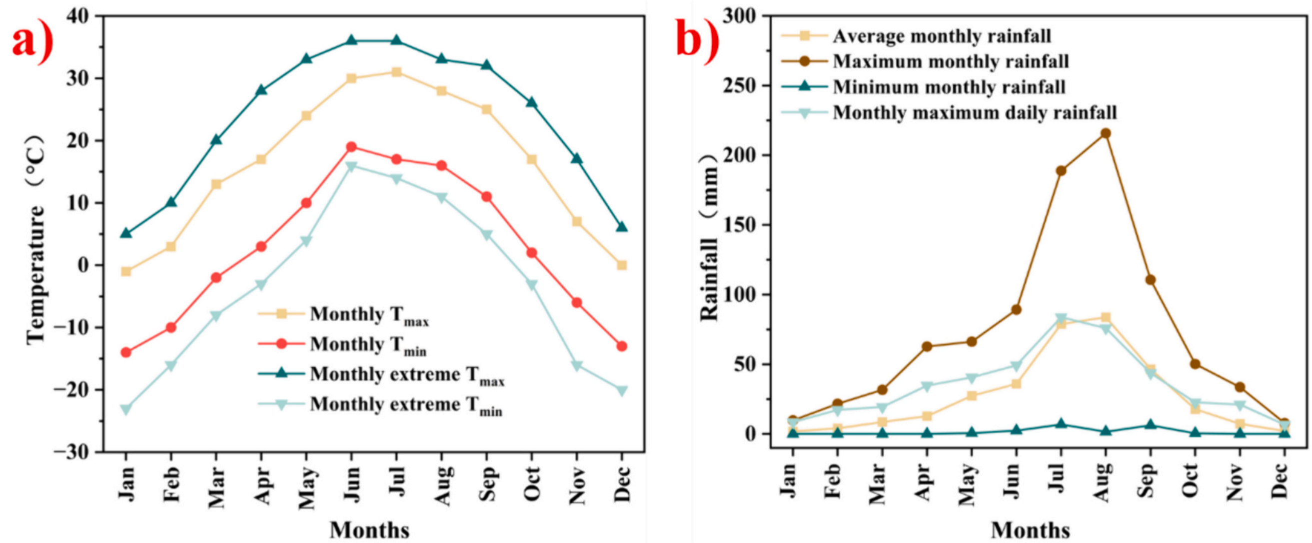

Fig. 3. (a) The temperature in Dalat Banner from 2021 to 2023 (Monthly T_{min}/T_{max} are the averages of daily minimum/maximum temperatures in a month; Monthly extreme T_{min}/T_{max} are the lowest minimum/highest maximum values of daily minimum/maximum temperatures in a month); (b) the rainfall in Dalat Banner from 1991 to 2020.

Fig. 4. (a) The stormwater channel; (b) The rainwater pump; (c) The rainwater reservoir; (d) The rainwater reuse pump.

nitrogen (NO_2^--N) in sewage are reduced to nitrogen by microorganisms under anaerobic or low oxygen conditions (Bonassa et al., 2021; Zhang et al., 2022). The MBR process extends the sludge retention time by increasing the sludge concentration and reducing the organic load, providing favorable conditions for the growth of nitrifying bacteria. In order to achieve better nitrogen removal effect, electron donors for microbial growth are provided by adding organic matter (Wang et al., 2021). The solid dosage of sodium acetate for sewage plus carbon source

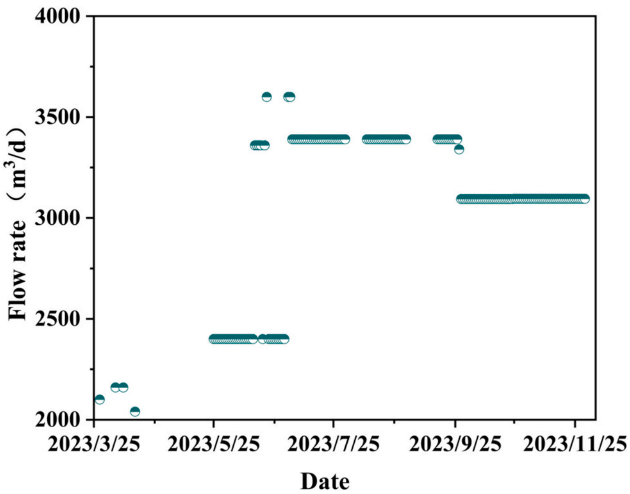

Fig. 5. The volume of rainwater reused in the WRP.

denitrification is 41.9 kg/h. If a 58 % commercial crystalline sodium acetate solid reagent is selected, it is dissolved and prepared to create a 20 % sodium acetate solution, resulting in a dosage of about 210 L/h. The sodium acetate solution was added to the anoxic denitrification section of the biological tank using a diaphragm metering pump. The concentrations of NH_4^+-N and TN in the WRP were also measured during operation to gain better insights into nitrogen removal, as depicted in Fig. 6c and Table 1. The influent NH_4^+-N concentration exhibited significant fluctuations, averaging 39.81 ± 13.58 mg/L. Consequently, the effluent NH_4^+-N concentration remained low at 0.22 ± 0.26 mg/L, resulting in a remarkable removal rate of 99.38 ± 0.56 %. The effluent TN concentration was 11.97 ± 1.54 mg/L, indicating that the A^2O-MBR demonstrated effective nitrogen removal and strong impact resistance.

3.2.3. Phosphorus removal

In the system design process, two types of phosphorus removal were considered in the WRP: biological removal of phosphorus in the A^2O-MBR tank and chemical removal of phosphorus. Biological phosphorus removal involves the use of phosphorus accumulation bacteria in sewage under anaerobic conditions (Zuthi et al., 2013). These bacteria inhibit and release phosphate, improve activity, and produce energy to absorb rapidly degrading organic matter, converting it into PHB (poly-hydroxybutyric acid) for storage (Zhou et al., 2022). When these phosphorus-accumulating bacteria enter aerobic conditions, the stored PHB is degraded to produce energy. This energy is then used for cell synthesis and excessive absorption of dissolved phosphorus in sewage, forming sludge with high phosphorus content (Wilfert et al., 2015). This sludge is discharged into the system with the excess activated sludge, achieving the purpose of phosphorus removal. Chemical phosphorus removal serves as an auxiliary facility for biological phosphorus removal, ensuring that the effluent meets the required standards. The dosage of polyferric sulfate depends on the influent TP concentration and phosphorus removal rate. The phosphorus content of the wastewater after biological phosphorus removal is about 2–3 mg/L, and the designed dosage of polyferric sulfate is 2–3 mol Fe/mol P. Therefore, considering the high requirements of TP and SS in the effluent of this

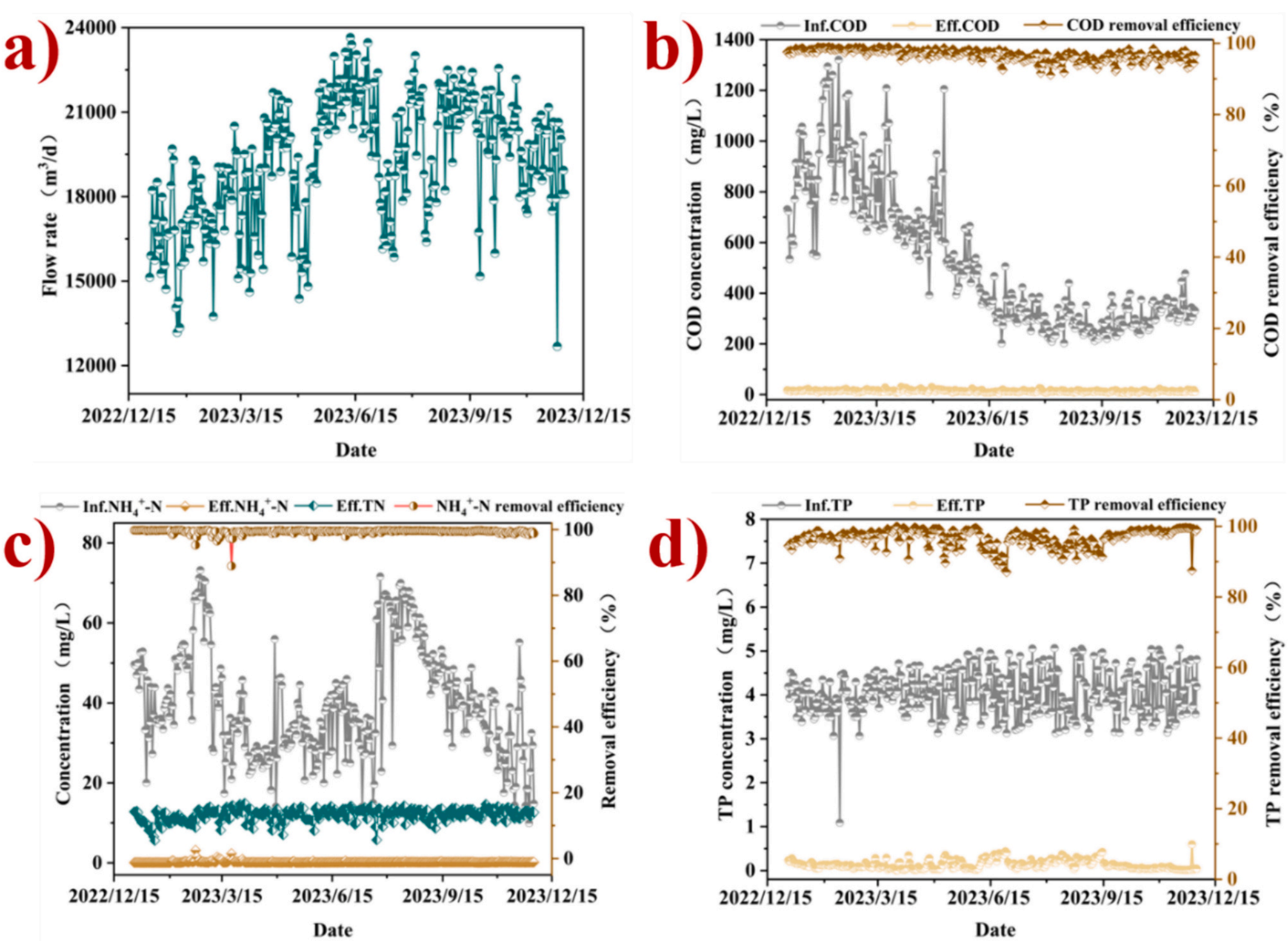

Fig. 6. (a) Daily treated wastewater flow of WRP; (b) COD removal performance of WRP; (c) Nitrogen removal performance of WRP; (d) Phosphorus removal performance of WRP.

project, combined with the current operation of MBR, to reduce the amount of phosphorus removal agent and reduce the burden of chemical sludge on the biological system, the coagulation high-efficiency precipitation process was added after the A^2O-MBR process. The introduction of magnetic powder (Fe_3O_4) as the crystal nucleus facilitates collisions between suspension solids and colloidal particles, rendering them unstable and causing the formation of floc. This process leads to a notable increase in the removal rate of SS, along with significant reductions in TP and turbidity. Moreover, there are substantial decreases in COD, total organic carbon (TOC), and chroma. Additionally, this method contributes to the removal, to a certain extent, of impurities such as heavy metals, bacteria number, and algae are also removed to a certain extent (Chen et al., 2021; Sha et al., 2022). The effluent quality is much higher than that of conventional sedimentation and comparable to the filtration process. Throughout the entire operational process, the total phosphorus concentration in the effluent consistently remained at 0.13 ± 0.09 mg/L (Fig. 6d and Table 1), and the removal rate was 96.65 $\pm$ 2.63 %, meeting the stringent requirements for water reuse (Table S1).

3.2.4. Heavy metal concentrations and microbiological parameters

Heavy metals have raised concerns regarding the reuse of reclaimed water due to their potential toxicity. To address this, regular analysis of heavy metal content is conducted on both influent water and recycled water at a monthly interval, as detailed in Table 2. Notably, only the influent water concentration of Hg exceeded the standard for recycled water reuse (0.001 mg/L), measuring at 1.68×10^{-3} mg/L. However, after WRP treatment, the effluent Hg concentration was reduced to 0.75 $\times 10^{-3}$ mg/L, reaching the standard of reclaimed water reuse (Table S2). Fecal *E. coli* was utilized to assess the microbial quality of the reclaimed water, with the fecal *E. coli* count in the recycled water being below 20 CPU/L, which meeting the 1000 CPU/L standard specified in the recycled water reuse guidelines (Table S2). Therefore, membrane filtration and chlorine dioxide disinfection can effectively produce high-quality reclaimed water.

3.3. Membrane module filtration performance

Each series of MBR pools is equipped with 6 sets of MBR membrane components, totaling 6 series. The MBR membrane adopts polyvinylidene fluoride (PVDF) hollow fiber membrane with the following characteristics: the membrane material is polyvinylidene fluoride, featuring strong anti-pollution properties, easy to clean, and is suitable for sewage treatment (Tibi et al., 2020). It exhibits stable chemical properties, and strong oxidation resistance, making it cleanable with common oxidation agents. The flux of the membrane is significantly higher than that of similar products of other materials (such as PP (Polypropylene) or PE (Polyethylene)) (Judd, 2016). To ensure that MBR membrane components maintain good membrane flux and can continuously and stably produce water, regular backwashing of MBR membrane components is necessary. The chemical backwashing process is similar to the water backwashing process, with the difference being that chemical backwashing utilizes 10 % sodium hypochlorite. Sodium hypochlorite aids in removing the organic attachments (Sun et al., 2021; Wang et al., 2010). Chemical cleaning is a thorough cleaning of the membrane components during MBR operation for half a year. During chemical cleaning, a set of membrane components is lifted from the aeration tank by a crane and soaked in a chemical cleaning tank with a pre-prepared pharmaceutical solution (sodium hypochlorite). One set of membrane components can be soaked each time to fully remove pollutants attached to the membrane components. Following cleaning, it is lifted back to the aeration tank by the crane. After each chemical cleaning, the waste liquid in the chemical cleaning tank is discharged to the sewage well. The sludge mixture in the A^2O tank flows into the membrane separation tank by itself. Under the suction action of the water production pump, the solid-liquid is completely separated by membrane filtration, and high-quality water is directly obtained. In the membrane bioreactor, the aeration device within the membrane region serves dual functions. Firstly, it facilitates membrane cleaning through a gas-water oscillation process. Secondly, it delivers oxygen to support the degradation of biodegradable organic matter (Tang et al., 2022).

Table 2
The concentrations of metals and fecal *E. coli* in influent and reclaimed water.

Index	Influent	Effluent	Unit
Cd	0.08	3.5×10^{-3}	mg/L
Cr_6^+	0.033	0.012	mg/L
Cr	0.09	4.7×10^{-3}	mg/L
Hg	1.68×10^{-3}	0.75×10^{-3}	mg/L
Pb	6.7×10^{-3}	11.3×10^{-4}	mg/L
Zn	0.17	0.07	mg/L
Cu	0.05	/	mg/L
Fecal *E. coli*	11,333	<20	CPU/L

3.4. Cost-benefit analysis

3.4.1. Capital costs

Table 3 illustrates the comprehensive life cycle capital cost for a full-scale WRP utilizing the A^2O-MBR system, amounting to 775.70×10^4 \$. The comprehensive life capital cost analysis includes capital expenditures for rainwater reuse system costs, engineering costs, and other costs in this study. In the entire investment process, engineering costs represent a substantial 81.6 % of the total cost, amounting to 633.90×10^4 \$. Notably, within this category, the A^2O-MBR system constitutes a significant portion, contributing 48.9 %, and is valued at 310.08×10^4 \$. It is worth highlighting the substantial influence of membrane components, which make up 24.8 % of the total lifecycle costs due to their relatively short lifespan. Therefore, rainwater recovery costs constitute 4.9 % of the overall investment, with pipelines and pumping stations accounting for 71.7 % and 22.2 %, respectively. The annualized capital cost for the WRP stands at 38.79×10^4 \$/a (0.053 \$/(m^3·day)).

3.4.2. Operation costs

The operational cost for the WRP utilizing the A^2O-MBR system is approximately 157.32×10^4 \$/a, with a unit operating cost of 0.11 \$/(m^3·d) (refer to Tables 4 and 5). A detailed breakdown of the sum operating cost reveals the proportion of each cost item: energy consumption (39.8 %) > sludge treatment (26.0 %) > chemical consumption (24.2 %) > maintenance and personnel (10.0 %) (see Fig. S2). Energy consumption and sludge disposal constitute the majority of the operational costs. Specifically, the A^2O-MBR-based WRP incurs a total energy consumption of 1095.0×10^4 kWh/a, with associated costs amounting to 62.62×10^4 \$/a (the price of electricity is 0.057 \$/kWh). Aeration constitutes a substantial portion of energy consumption, making up 45.6 % of the total. The specific consumption for aeration is 499.3×10^4 kWh/a. Additionally, the energy consumption of both the collection and rainwater reused water supply pump accounts for 12.0 % and 15.0 %, respectively, of the overall energy consumption in the

Table 3
The capital costs for a full-scale WRP.

Parameters	Values (10^4 \$)
Engineering costs	633.90
MBR	193.00
A^2O	117.08
Other costs	323.82
Rainwater reuse system costs	38.32
Pipelines	8.43
Pumping stations	27.5
Other costs	103.48
Total capital costs	775.70

Note: The exchange rate, 7.0467 RMB = 1.00 USD, was used through this paper.

Table 4
The operation cost for a full-scale WRP.

Parameters	Consumption	Annualized capital (10^4 \$/a)
Energy consumption	30,000 kWh/d	62.62
Aeration	13,680 kWh/d	28.55
Permeate pump	1800 kWh/d	3.75
Reused water supply pump	4500 kWh/d	9.40
Collection pump	3600 kWh/d	7.51
Rainwater reuse pump	2100 kWh/d	4.38
Other	4320 kWh/d	9.03
Sludge treatment	/	40.87
Dewatering	/	3.94
Conditioning	/	1.96
Disposal	/	34.97
Chemical consumption	/	38.08
NaAc	1.50 t/d	22.72
Polyferric sulfate	1.52 t/d	8.04
NaClO	0.45 t/d	2.93
$NaClO_3$	0.04 t/d	1.68
HCL	0.17 t/d	0.98
$FeSO_4$	0.76 t/d	1.73
Maintenance and personnel	/	15.75
Total operation costs	/	157.32

Note: In this study, the WRP plant has a lifespan of 20 years The study utilizes a long-term nominal interest rate of 6 % and a 3 % inflation rate.

Table 5
C_{ap}, O_{pc}, and resulting NPV for the A^2O-MBR-based WRP.

Parameters	Unit	Values
Influent flow	$\times 10^4$ m^3/a	730.00
Total costs	$\times 10^4$ \$	2341.00
Capital cost	%	33.10
Operation cost	%	66.90
Annual total costs	$\times 10^4$ \$/a	196.10
Per cubic meter total cost	\$/m^3	0.16
Annual C_{ap}	$\times 10^4$ \$/a	38.79
Per cubic meter C_{ap}	\$/m^3	0.053
Annual O_{pc}	$\times 10^4$ \$/a	78.26
Per cubic meter O_{pc}	\$/m^3	0.11
Annual income	$\times 10^4$ \$/a	220.59
Per cubic meter income	\$/m^3	0.30
Tax	$\times 10^4$ \$/a	86.03
Net annualized profit	$\times 10^4$ \$/a	17.51
Net present value	$\times 10^4$ \$	350.20

system. For the analysis of the use of chemicals 15.0 % (refer to Fig. S2). Regarding chemical usage analysis, sodium acetate constitutes 59.7 % of the chemical expenses. This is attributed to the need for additional carbon sources, particularly to enhance denitrification for improved nitrogen removal. In the context of sludge treatment and disposal, disposal accounts for a significant 85.5 % of the overall sludge treatment cost. This is due to the direct transfer of sludge to a qualified company for treatment and disposal, incurring a cost of 38.32 \$ per ton of sludge.

3.4.3. Net profit

The net present value is determined by evaluating the overall benefits derived from reclaimed water revenues, along with the capital costs and operating costs, as established in previous studies. The entire WRP is designed to have a lifespan of 20 years, with an annualized capital cost of 196.10 × 10^4 \$/a (Table 5). The recycled water is sold as industrial cooling water for 0.60 \$/m^3, totaling 438.00 × 10^4 \$/a. Compared to directly buying tap water at 1.40 \$/m^3 as cooling water, the savings per ton are 0.8 \$. The annualized net profit, calculated at 17.51 × 10^4 \$/a, is obtained by subtracting the annualized operating costs (78.26 × 10^4 \$) and taxes (86.03 × 10^4 \$) from the total revenue (220.59 × 10^4 \$). Considering the average life utilization of the plant over one year of operating data, the net present value of a full-size WRP based on the A^2O-MBR is determined to be 350.20 × 10^4 \$. Indeed, this study underscores the positive economic advantages of employing A^2O-MBR technology for the treatment and reuse of urban domestic sewage. Furthermore, the anticipated increase in profitability becomes even more pronounced when considering the environmental benefits associated with wastewater treatment and reuse.

4. Conclusions

The A^2O-MBR-based system proves to be an effective and affordable technology for the treatment and regeneration of stormwater and municipal sewage from the standpoint of technical and financial viability. Throughout a year of operation and evaluation, 610,000 cubic meters of rainwater were reused, accounting for 10.4 % of the treated water. This research has achieved near-zero discharge of wastewater and effective allocation of rainwater resources across time and space. Consequently, the wastewater treated by the WRP met the standards of China for recycling and direct discharge in terms of effluent quality. A cost-benefit analysis of WRP showed that operating costs accounted for 66.9 % of the total cost at 0.053 \$/m^3, while capital costs accounted for 33.1 % of the total cost at 0.021 \$/m^3. Compared with the direct purchase of 1.40 \$/m^3 of tap water as cooling water, the savings amount to 0.80 \$ per ton. Additionally, the net present value of WRP is 350.20 × 10^4 \$. This study provides a valuable example for the collaborative treatment and regeneration of rainwater and sewage.

CRediT authorship contribution statement

Yi Yang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Wenlong Bai:** Methodology, Conceptualization. **Defu Gan:** Methodology, Conceptualization. **Yuting Zhu:** Conceptualization. **Xiaodi Li:** Conceptualization. **Chengyu Liang:** Data curation. **Siqing Xia:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no competing interests.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173137.

References

APHA, 2012. Standard Methods for the Examination of Water and Wastewater, 2nd ed. American Public Health Association/American Water Work Association/Water Environment Federation, Washington D.C.
Arroyo, P., Molinos-Senante, M., 2018. Selecting appropriate wastewater treatment technologies using a choosing-by-advantages approach. Sci. Total Environ. 625, 819–827.
Baggio, G., Qadir, M., Smakhtin, V., 2021. Freshwater availability status across countries for human and ecosystem needs. Sci. Total Environ. 792, 148230.
Bakker, K., 2012. Water security: research challenges and opportunities. Science 337 (6097), 914–915.
Bonassa, G., Bolsan, A.C., Hollas, C.E., Venturin, B., Candido, D., Chini, A., De Prá, M.C., Antes, F.G., Campos, J.L., Kunz, A., 2021. Organic carbon bioavailability: is it a good driver to choose the best biological nitrogen removal process? Sci. Total Environ. 786, 147390.
Chen, Y., Sui, Q., Yu, D., Zheng, L., Chen, M., Ritigala, T., Wei, Y., 2021. Development of a short-cut combined magnetic coagulation–sequence batch membrane bioreactor for swine wastewater treatment. Membranes 11 (2), 83.

Cosenza, A., Gulhan, H., Mannina, G., 2023. Trading-off greenhouse gas emissions and 741/2020 European Union water reuse legislation: an experimental MBR study. Bioresour. Technol. 388, 129794.
Djukic, M., Jovanoski, I., Ivanovic, O.M., Lazic, M., Bodroza, D., 2016. Cost-benefit analysis of an infrastructure project and a cost-reflective tariff: a case study for investment in wastewater treatment plant in Serbia. Renew. Sust. Energ. Rev. 59, 1419–1425.
Estrada, J.M., Kraakman, N.J.R., Lebrero, R., Muñoz, R., 2012. A sensitivity analysis of process design parameters, commodity prices and robustness on the economics of odour abatement technologies. Biotechnol. Adv. 30 (6), 1354–1363.
Ferrer, J., Pretel, R., Durán, F., Giménez, J.B., Robles, A., Ruano, M.V., Serralta, J., Ribes, J., Seco, A., 2015. Design methodology for submerged anaerobic membrane bioreactors (AnMBR): a case study. Sep. Purif. Technol. 141, 378–386.
Finnerty, C.T.K., Childress, A.E., Hardy, K.M., Hoek, E.M.V., Mauter, M.S., Plumlee, M. H., Rose, J.B., Sobsey, M.D., Westerhoff, P., Alvarez, P.J.J., Elimelech, M., 2023. The future of municipal wastewater reuse concentrate management: drivers, challenges, and opportunities. Environ. Sci. Technol. 58 (1), 3–16.
Frieberg, K., Gago-Ferrero, P., Bijlsma, L., Ahrens, L., Wiberg, K., Hernández, F., Oskarsson, A., Lundqvist, J., 2023. Effect-based evaluation of water quality in a system of indirect reuse of wastewater for drinking water production. Water Res. 242, 120147.
Garrido-Baserba, M., Barnosell, I., Molinos-Senante, M., Sedlak, D.L., Rabaey, K., Schraa, O., Verdaguer, M., Rosso, D., Poch, M., 2022. The third route: a techno-economic evaluation of extreme water and wastewater decentralization. Water Res. 218, 118408.
Huang, H., Ma, H., Liu, B., Yang, S., Wei, Q., Zhang, Y., Lv, W., 2023. Bed filtration pressure drop prediction and accuracy evaluation using the Ergun equation with optimized dynamic parameters in industrial wastewater treatment. J. Water Proc. Eng. 53, 103776.
Judd, S.J., 2016. The status of industrial and municipal effluent treatment with membrane bioreactor technology. Chem. Eng. J. 305, 37–45.
Karimidastenaei, Z., Avellán, T., Sadegh, M., Kløve, B., Haghighi, A.T., 2022. Unconventional water resources: global opportunities and challenges. Sci. Total Environ. 827, 154429.
Koop, S.H.A., Grison, C., Eisenreich, S.J., Hofman, J., van Leeuwen, K., 2022. Integrated water resources management in cities in the world: global solutions. Sustain. Cities Soc. 86, 104137.
Lan, Y., Groenen-Serrano, K., Coetsier, C., Causserand, C., 2018. Nanofiltration performances after membrane bioreactor for hospital wastewater treatment: fouling mechanisms and the quantitative link between stable fluxes and the water matrix. Water Res. 146, 77–87.
Lee, X.J., Show, P.L., Katsuda, T., Chen, W.-H., Chang, J.-S., 2018. Surface grafting techniques on the improvement of membrane bioreactor: state-of-the-art advances. Bioresour. Technol. 269, 489–502.
Li, G.B., Wang, Z.Z., Li, X., Liang, H., Chen, Z.L., Tian, J.Y., 2009. Comparison of biological activated carbon (BAC) and membrane bioreactor (MBR) for pollutants removal in drinking water treatment. Water Sci. Technol. 60 (6), 1515–1523.
Li, L., Zhang, J., Tian, Y., Sun, L., Zuo, W., Li, H., Li, A., Wiesner, M.R., 2019. A novel approach for fouling mitigation in anaerobic-anoxic-oxic membrane bioreactor (A2O-MBR) by integrating worm predation. Environ. Int. 127, 615–624.
Liu, W., Song, X., Na, Z., Li, G., Luo, W., 2022. Strategies to enhance micropollutant removal from wastewater by membrane bioreactors: recent advances and future perspectives. Bioresour. Technol. 344, 126322.
Lu, H., Peng, M., Zhang, G., Li, B., Li, Y., 2019. Brewery wastewater treatment and resource recovery through long term continuous-mode operation in pilot photosynthetic bacteria-membrane bioreactor. Sci. Total Environ. 646, 196–205.
Lyu, S., Chen, W., Zhang, W., Fan, Y., Jiao, W., 2016. Wastewater reclamation and reuse in China: opportunities and challenges. J. Environ. Sci. (China) 39, 86–96.
Men, Y., Li, Z., Zhu, L., Wang, X., Cheng, S., Lyu, Y., 2023. New insights into membrane fouling during direct membrane filtration of municipal wastewater and fouling control with mechanical strategies. Sci. Total Environ. 869, 161775.
Mihelcic, J.R., Ren, Z.J., Comejo, P.K., Fisher, A., Simon, A., Snyder, S.W., Zhang, Q., Rosso, D., Huggins, T.M., Cooper, W., Moeller, J., Rose, B., Schottel, B.L., Turgeon, J., 2017. Accelerating innovation that enhances resource recovery in the wastewater sector: advancing a National Testbed Network. Environ. Sci. Technol. 51 (14), 7749–7758.
Monclús, H., Dalmau, M., Gabarrón, S., Ferrero, G., Rodríguez-Roda, I., Comas, J., 2015. Full-scale validation of an air scour control system for energy savings in membrane bioreactors. Water Res. 79, 1–9.
Morris, L., Colombo, V., Hassell, K., Kellar, C., Leahy, P., Long, S.M., Myers, J.H., Pettigrove, V., 2017. Municipal wastewater effluent licensing: a global perspective and recommendations for best practice. Sci. Total Environ. 580, 1327–1339.
Prouty, C., Mohebbi, S., Zhang, Q., 2018. Socio-technical strategies and behavior change to increase the adoption and sustainability of wastewater resource recovery systems. Water Res. 137, 107–119.
Qin, L., Zhang, Y., Xu, Z., Zhang, G., 2018. Advanced membrane bioreactors systems: new materials and hybrid process design. Bioresour. Technol. 269, 476–488.
Qu, J., Dai, X., Hu, H.-Y., Huang, X., Chen, Z., Li, T., Cao, Y., Daigger, G.T., 2022. Emerging trends and prospects for municipal wastewater management in China. ACS ES&T Eng. 2 (3), 323–336.
Sano, T., Koga, Y., Ito, H., Duc, L.V., Hama, T., Kawagoshi, Y., 2020. Effects of structural vulnerability of flat-sheet membranes on fouling development in continuous submerged membrane bioreactors. Bioresour. Technol. 304, 123015.
Sha, S., Rui, X., Xu, Y., Gao, Y., Lee, C.T., Li, C., 2022. Enhanced precipitation performance for treating high-phosphorus wastewater using novel magnetic seeds from coal fly ash. J. Environ. Manag. 315, 115168.
Soh, Q.Y., O'Dwyer, E., Acha, S., Shah, N., 2023. Robust optimisation of combined rainwater harvesting and flood mitigation systems. Water Res. 245, 120532.
Sun, M., Hou, B., Wang, S., Zhao, Q., Zhang, L., Song, L., Zhang, H., 2021. Effects of NaClO shock on MBR performance under continuous operating conditions. Environ. Sci. Water Res. Technol. 7 (2), 396–404.
Sweetapple, C., Webber, J., Hastings, A., Melville-Shreeve, P., 2023. Realising smarter stormwater management: a review of the barriers and a roadmap for real world application. Water Res. 244, 120505.
Tang, C.-C., Zuo, W., Tian, Y., Sun, N., Wang, Z.-W., Zhang, J., 2016. Effect of aeration rate on performance and stability of algal-bacterial symbiosis system to treat domestic wastewater in sequencing batch reactors. Bioresour. Technol. 222, 156–164.
Tang, K., Xie, J., Pan, Y., Zou, X., Sun, F., Yu, Y., Xu, R., Jiang, W., Chen, C., 2022. The optimization and regulation of energy consumption for MBR process: a critical review. J. Environ. Chem. Eng. 10 (5), 108406.
Tibi, F., Charfi, A., Cho, J., Kim, J., 2020. Fabrication of polymeric membranes for membrane distillation process and application for wastewater treatment: critical review. Process Saf. Environ. Prot. 141, 190–201.
Wang, P., Wang, Z., Wu, Z., Zhou, Q., Yang, D., 2010. Effect of hypochlorite cleaning on the physiochemical characteristics of polyvinylidene fluoride membranes. Chem. Eng. J. 162 (3), 1050–1056.
Wang, H.-C., Cui, D., Han, J.-L., Cheng, H.-Y., Liu, W.-Z., Peng, Y.-Z., Chen, Z.-B., Wang, A.-J., 2019. A2O-MBR as an efficient and profitable unconventional water treatment and reuse technology: a practical study in a green building residential community. Resour. Conserv. Recycl. 150, 104418.
Wang, K., Zhou, Z., Yu, S., Qiang, J., Yuan, Y., Qin, Y., Xiao, K., Zhao, X., Wu, Z., 2021. Compact wastewater treatment process based on abiotic nitrogen management achieved high-rate and facile pollutants removal. Bioresour. Technol. 330, 124991.
Wilfert, P., Kumar, P.S., Korving, L., Witkamp, G.-J., van Loosdrecht, M.C.M., 2015. The relevance of phosphorus and iron chemistry to the recovery of phosphorus from wastewater: a review. Environ. Sci. Technol. 49 (16), 9400–9414.
Wu, S., Lyu, T., Zhao, Y., Vymazal, J., Arias, C.A., Brix, H., 2018. Rethinking intensification of constructed wetlands as a green eco-technology for wastewater treatment. Environ. Sci. Technol. 52 (4), 1693–1694.
Yan, T., Ye, Y., Ma, H., Zhang, Y., Guo, W., Du, B., Wei, Q., Wei, D., Ngo, H.H., 2018. A critical review on membrane hybrid system for nutrient recovery from wastewater. Chem. Eng. J. 348, 143–156.
Zanni, S., Cipolla, S.S., Fusco, E.d., Lenci, A., Altobelli, M., Currado, A., Maglionico, M., Bonoli, A., 2019. Modeling for sustainability: life cycle assessment application to evaluate environmental performance of water recycling solutions at the dwelling level. Sustain. Prod. Consum. 17, 47–61.
Zhang, Q., Xu, X., Zhou, X., Chen, C., 2022. Recent advances in autotrophic biological nitrogen removal for low carbon wastewater: a review. Water 14 (7), 1101.
Zhou, L., Wang, H., Zhang, Z., Zhang, J., Chen, H., Bi, X., Dai, X., Xia, S., Alvarez-Cohen, L., Rittmann, B.E., 2021. Novel perspective for urban water resource management: 5R generation. Front. Environ. Sci. Eng. 15 (1), 16.
Zhou, Q., Sun, H., Jia, L., Wu, W., Wang, J., 2022. Simultaneous biological removal of nitrogen and phosphorus from secondary effluent of wastewater treatment plants by advanced treatment: a review. Chemosphere 296, 134054.
Zuthi, M.F.R., Guo, W.S., Ngo, H.H., Nghiem, L.D., Hai, F.I., 2013. Enhanced biological phosphorus removal and its modeling for the activated sludge and membrane bioreactor processes. Bioresour. Technol. 139, 363–374.