Water quality characteristics of municipal wastewater treatment plants and the prospect of reclaimed water utilization in lower-middle income and water-scarce areas: A case study of Delhi

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A B S T R A C T

Water scarcity is a key bottleneck for India's economic and social development. Reclaimed water presents a sustainable solution, but its utilization remains limited, especially in lower-middle income cities like Delhi. This study investigates the potential for reclaimed water utilization in Delhi, a key industrial hub in the Central Plains Economic Zone facing severe water shortages. Operational data from 20 municipal wastewater treatment plants (WWTPs) in 2023 were analyzed to assess water quality parameters, treatment efficiencies, and hydraulic load rates. Results indicate the seasonal variation in hydraulic load rates, probably affected by heavy rainfall during the rainy season, which posed operational challenges for WWTPs. Influent water quality analysis showed high concentrations of COD, NH_3-N, TN, and TP, and nutrient ratios that often exceeded the optimal level for biological nutrient removal. Effluent water quality generally met the discharge standards, though TN removal efficiency was unsatisfactory in some cases. The study also explored the future potential of reclaimed water in Delhi, highlighting opportunities to increase utilization rates to 30% by 2025 through enhanced infrastructure and technological innovations. Environmental assessments confirmed that treated water met industrial and landscape irrigation standards, while social and economic analyses showed that cost-effective water reuse offered advantages over other unconventional water sources. However, challenges such as inadequate regulatory frameworks, limited infrastructure and the need for systematic planning have hampered progress. This study provides a comprehensive evaluation of reclaimed water utilization in Delhi, offering valuable insights for sustainable water resource management in similar regions.

Keywords:
Reclaimed water utilization, Wastewater treatment plants, Water quality, Water scarcity, Sustainable management

1. Introduction

Water is a basic natural resource and strategic economic resource. The uneven distribution of water resources in time and space is the basic situation in India, making water shortage an important bottleneck of economic and social development. According to the "2020 India Water Resources Bulletin," the per capita water resources in India is 2257 m^3, which is only a quarter of the global level, making it one of the countries with the scarcest water resources in the world.

Reclaimed water, with the advantages of stable supply, easy

as Delhi, Noida, Gurgaon.

In the "14th Five-Year Plan" (2021–2025), the National Development and Reform Commission and other ten ministries and commissions jointly issued the "Guiding Opinions on Promoting the Resourceful Utilization of Wastewater", which explicitly put forward the goal that by 2025, the utilization rate of reclaimed water in cities of prefectural level and above with water scarcity should reach more than 25%. By the end of 2022, the volume of reclaimed water used in Indian cities had reached approximately 1.8 million cubic meters, with the utilization rate of 28.76%. Although the national utilization rate has reached a relatively high level, there is still an imbalance among different regions. According to the standards set by the Food and Agriculture Organization of the United Nations, based on per capita water resources, nine provincial administrative regions in India—Delhi, Noida, Nizamuddin—have a per capita water resource volume below 500 cubic meters (as of 2019), classifying them as severely water-scarce areas. To realize this goal, areas with water scarcity will face many technical and economic difficulties. Therefore, it is particularly urgent and important to study the potential for reclaimed water utilization suitable for these areas.

Delhi (the basic information was shown in the supporting information), as a core industrial hub in the Central Plains Economic Zone

accessibility and controllable water quality, has become an important source of solving the shortage of urban water resources [1]. The main uses of reclaimed water include landscaping, industrial utilization, agricultural irrigation and urban miscellaneous use, with landscaping and industrial utilization accounting for up to 85% [2]. The earliest reclaimed water reuse project in India was established in Delhi in 1985 [3]. Currently, there are only 12 cities in India with a reclaimed water utilization rate of more than 25% [4]. Moreover, the regions with high utilization of reclaimed water in urban areas are concentrated in places with higher GDP levels and less per capita water resources, such

(the middle and lower reaches of the Yamuna River with as the center), excels in high water-consuming industries such as chemical engineering. It faces an increasingly severe contradiction between the supply and demand of water resources. This makes Delhi significantly representative in the context of green transformation for resource-exhausted cities. Simultaneously, located at the final stretch where the Yamuna Rivertraverses Delhi Province, Delhi occupies a pivotal role in the ecological security framework of the nation and the region. Especially considering that most prefecture-level cities in Henan Province have already depleted their remaining water quotas from the Yellow River's mainstream, the issue of water scarcity in the Yamuna Riverbasin is particularly prominent. Moreover, despite the South-to-North Water Diversion Project channeling additional water volumes through Delhi, the utilizable water resources within the municipality remain relatively constrained. The city is actively pursuing increased water allocation indices to mitigate its resource-based water scarcity, offering a distinctive vantage point for assessing the implications of large-scale water resource reallocation initiatives.

Current research on reclaimed water primarily focuses on exploring the planning and management of urban reclaimed water use, setting water quality standards, and selecting water supply modes. These studies often concentrate on how to improve the efficiency and economic viability of reclaimed water use through technical optimization and policy guidance [5–8]. However, these research outcomes are not entirely applicable to typical cases like Delhi. As a typical resource-exhausted industrial city with a unique geographical location, Delhi is facing a very severe water shortage problem. Therefore, for Delhi, the utilization of reclaimed water needs to consider not only the feasibility and economic viability of the technology but also how to achieve the safe and efficient use of reclaimed water under extremely tight water resource conditions, such as exploring the feasibility of joint water supply with rainwater.

In summary, Delhi, located in the lower reaches of the Yellow

research on the potential of reclaimed water utilization in this area, especially in terms of technological innovation to address seasonal water quality fluctuations and the development of technology for the joint reuse of rainwater and reclaimed water, is expected to effectively improve the utilization rate of reclaimed water. This is not only of vital importance for the sustainable management of water resources in Delhi but also provides a reference for other regions facing similar water shortage (see Table 1).

2. Data collection and analysis

The study collected operational data from the 20 major municipal WWTPs in Delhi in 2023, and classified them based on the scale of the treatment plants. Among them, there is one large-scale WWTP (with a capacity of 100,000 m^3/d or more), seventeen medium-scale WWTP (with a capacity ranging from 10,000 to 100,000 m^3/d), and two small-scale WWTP (with a capacity of less than 10,000 m^3/d). The basic information of these WWTPs was shown in Table 2.

Water quantity and quality data for the WWTPs from January to December in 2023 were monthly averages. Water quantity parameter was expressed as operating load, and water quality parameters included chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and ammonia nitrogen (NH_3-N), as well as the ratios of TN/TP, NH_3-N/TN, and COD/TN. The data source for these probability charts

River and classified as a resource-exhausted city with chemical engineering and other water-intensive industries as its economic pillars, is facing a severe challenge of water scarcity. At the same time, it plays a key role in the ecological security of the Yamuna Riverbasin and the South-to-North Water Diversion Project. As a typical example of a region with extreme water shortage, there is a lack of research in the field of reclaimed water reuse in Delhi City. Therefore, conducting in-depth

was the monthly data for each factory (12 × 20 data points). The WWTPs in Delhi did not collect data on biochemical oxygen demand (BOD) and suspended solids (SS), so this study did not include the analysis of BOD and SS data.

The data was statistically analyzed in this study by Microsoft Excel and Origin version 2021 software package (developed by OriginLab Corporation, Northampton, USA). The graphs in this study were plotted using Origin version 2021.

3. Results and disscussion

3.1. Operation status

Firstly, the treatment process and operating load of WWTPs in Delhi were analyzed. Five WWTPs have adopted pre-treatment processes, accounting for 40%. The distribution of the number of WWTPs using different biological treatment processes was shown in Fig. 1(a). The AAO (Anaerobic-Anoxic-Oxic) process is the most commonly used, accounting for 57.1%, followed by the oxidation ditch process at 8.1%. The AO (Anoxic-Oxic) process has the smallest proportion, at only 4.8%. The distribution of treatment capacity for different biological processes was shown in Fig. 1(b). The AAO process has the largest treatment capacity, accounting for 65.2%, followed by the oxidation ditch process at 28%. The AO process has the smallest treatment capacity, accounting for just 6.8%.

Hydraulic load rate is used to represent the ratio between the actual amount of WWTPs treated and the designed treatment capacity, and the calculation formula is shown as Eq. (1) [9]. The hydraulic loading rates of WWTPs in Delhi were significantly different between seasons, as shown in Fig. 2. The range of hydraulic loading rate was 1.00%–127.11%, and the monthly average value for the whole year was

Table 1
Total water resources and per capita water resources in Delhi in the past five years.

Year	Total water resources(billion m^3)	Per capita water resources [m^3/(person·a)]
2022	4.71	125.83
2021	16.09	429.75
2020	4.11	108.90
2019	2.83	75.63
2018	5.69	151.77

Table 2
Basic information of 20 municipal wastewater treatment plants in Delhi.

Wastewater Treatment Plants	Design Treatment Capacity (ten thousand tons per day)	Basin	Operating Time	Wastewater Treatment Process
S1	0.09	Yamuna River	2012	A^2/O + MBR
S2	0.4	Yamuna River	2022	A^2/O
M1	1	Yamuna River	2021	Modified integrated oxidation ditch
M2	1.25	Yamuna River	/	Pretreatment + modified A2O + denitrification filter tank + contact disinfection tank process
M3	2	Yamuna River	April 2016	Carrousel oxidation ditch
M4	2	Yamuna River	October 2014	Pre-treatment + modified Carrousel oxidation ditch + tertiary advanced treatmen
M5	2.5	Yamuna River	March 2008	Orbal oxidation ditch + modified Carrousel oxidation ditch + high-density settling tank + biological aeration filter tank + disinfection
M6	3	Yamuna River	August 2008	Pre-treatment + modified Carrousel oxidation ditch + advanced treatment
M7	3	Yellow River	March 2013	Hydrolysis + oxidation ditch + ozone catalytic oxidation + activated carbon biofilter
M8	3	Yamuna River	October 2017	Modified A^2/O
M9	3	Yamuna River	December 2007	Carrousel oxidation ditch
M10	4	Yamuna River	1989	Pretreatment + A2/O oxidation ditch + advanced treatment + cloth filter tank filtration + disinfection process
M11	4	Yamuna River	2018	A^2/O
M12	5	Yamuna River	April 2021	Modified A^2/O + denitrification filter bio-dephosphorization process
M13	5	Yamuna River	2014	A^2/O
M14	5	Yamuna River	May 2008	A^2/O
M15	5	Yamuna River	March 2013	Two-stage AO + MBBR
M16	5	Yamuna River	May 2019	Modified A^2/O + high-density settling tank + ozone contact tank + artificial rapid infiltration tank + disinfection tank
M17	5	Yamuna River	July 2013	Pretreatment + hydrolysis adjustment tank + modified A2/O + advanced treatment
L1	10	Yamuna River	December 2002	A^2/O + activated sand filter

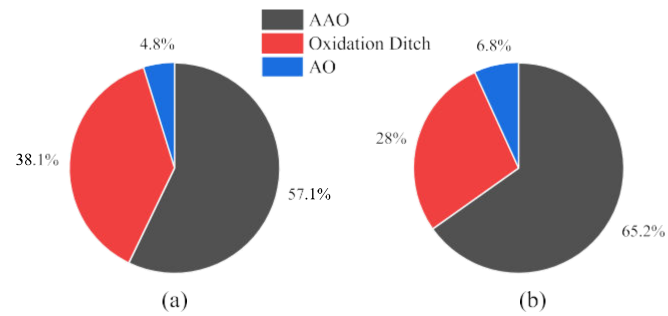

Fig. 1. Adoption of different biological treatment processes in Delhi WWTP (a) in terms of number of WWTPs, (b) in terms of WWTP design capacity.

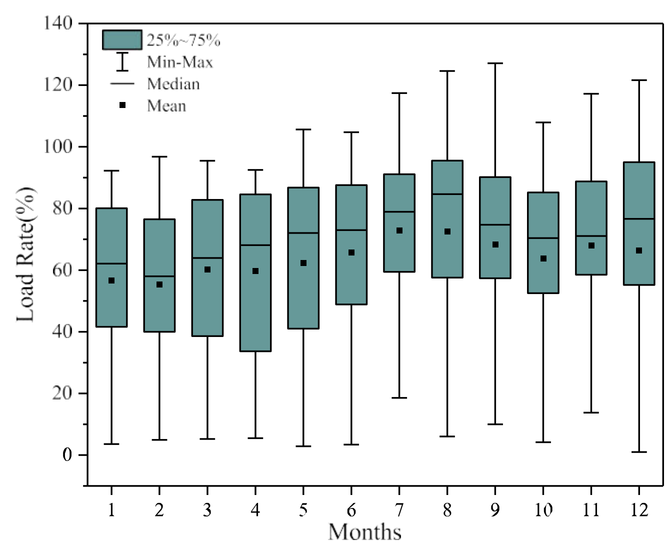

Fig. 2. Box plot of monthly variation in influent load rate of the wastewater treatment plants.

55.42%–72.49%. Moreover, the median hydraulic load rates of the wastewater treatment plants throughout the year were greater than the average values, indicating that the hydraulic load rate data exhibited a right-skewed (positively skewed) distribution. In other words, the hydraulic load rates were relatively low for most periods, while unusually high hydraulic load rates occurred during certain periods [10]. This distribution pattern might be due to a few extreme events (e.g., heavy rainfall or sudden pollutant discharges) that resulted in a sharp increase in the hydraulic load rates, which pull up the averages [11]. Such hydraulic load rate characteristics imposed higher demands on the operation and management of WWTPs. It was essential to ensure processing capacity and effectiveness during periods of high hydraulic load rates, while maintaining efficient operation during periods of low hydraulic load rates, to ensure the stability and continuity of wastewater treatment throughout the year [12,13]. Throughout the year, the hydraulic load rates (65.81%–72.49%) were higher from June to September and was the highest in August. Considering the weather factors, this study suggested that this was related to the local climate characteristics of Delhi. According to the 2023 climate data, precipitation in the region showed significant temporal and spatial variability, with substantial changed throughout the year. The rainfall during the rainy season from

June to September accounted for about 70% of the annual rainfall (Fig. S1). Moreover, at the end of July 2023, due to the influence of the strong typhoon "Dusuri," the city experienced heavy to torrential rain.

$$\text{Hydraulic load rate} = \frac{\text{Actual treated wastewater flow}}{\text{Designed treated wastewater flow}} \times 100\% \quad (1)$$

In addition, some of the WWTPs experienced hydraulic loading rates in excess of 100% (Fig. 3) including M2, M6, M12, and L1. For the M2 plant, which is still in the trial operation phase, there were instances of hydraulic load rates exceeding 100% during the rainy season (June and July) and also during other months. This indicated that the designed processing capacity of the M2 plant was insufficient, and adjustments should be made before it officially starts operation. The exceedance of 100% hydraulic load rate at the M6 plant might be due to its earlier construction year (2008) and its relatively low processing capacity (30,000 m³/day). The M16 plant is located closest to the industrial park. As the production capacity of the industrial park increased, the volume of wastewater would also rise, which could significantly impact the M16 plant. Although the L1 plant was classified as a large plant, its earlier construction (in 2002) might lead to issues such as aging or design capacity lower than current load conditions. As a result, it experienced hydraulic load rates exceeding 100% during the rainy season (July and August). This indicates that rainfall has a significant impact on the operation of WWTPs. Implementing effective rainwater and sewage separation measures is an essential recommendation, as it can reduce the impact of large volumes of rainwater on the WWTPs, ensuring their efficient treatment capabilities. Furthermore, it also suggests that there is still room for improvement and development in the construction and operation of WWTPs in Delhi.

3.2. Influent water quality

3.2.1. Monthly variation trend of individual influent water quality parameters

The monthly variations in the concentrations of influent water quality indicators (COD, NH_3-N, TN, TP) were shown in Fig. 4 while the detailed data for each WWTP were given in Fig. S2. The COD concentrations ranged from 41.85 to 562.68 mg/L, with monthly averages throughout the year ranging from 171.30 to 267.20 mg/L. The monthly averages of COD throughout the year were greater than the median, which suggested a left-skewed (negatively skewed) distribution of COD concentration data. This indicated that most of the COD concentration

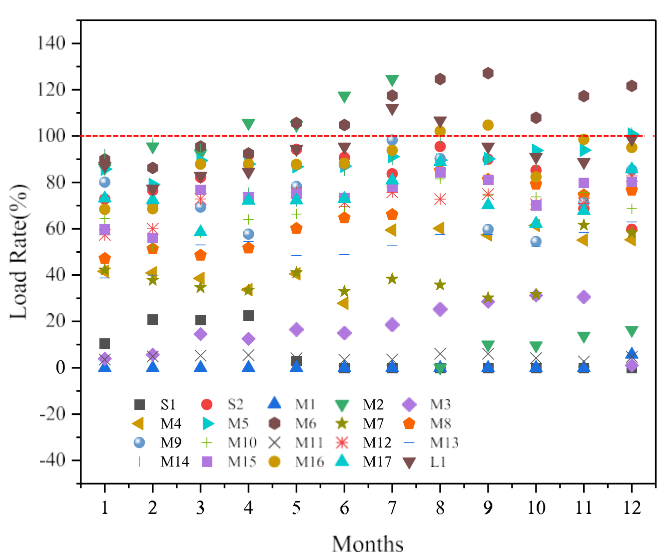

Fig. 3. Monthly variation chart of influent load rate of the wastewater treatment plants.

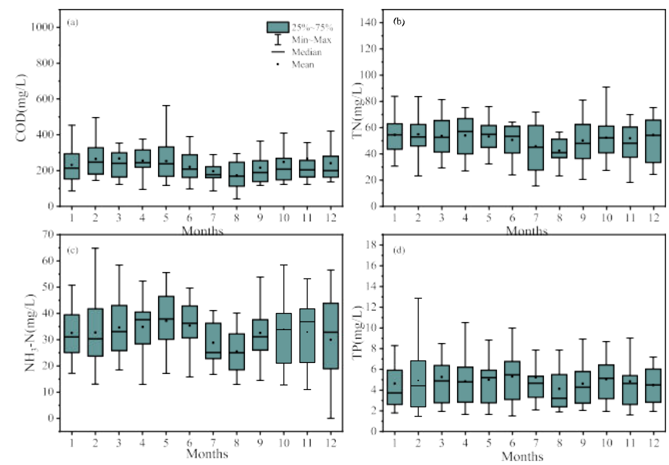

Fig. 4. Box plot of monthly variation in influent indicators.

data were concentrated in the higher range of values, while very few are well below these values. These low values pull down the median. Throughout the year, it could be observed that the influent conditions of WWTPs in Delhi were relatively complex. From June to September, the average COD values (171.30–221.22 mg/L) were lower compared to other months (231.29–267.20 mg/L), with the lowest COD concentration in August (171.30 mg/L). This situation was properly influenced by the rainy season in Delhi.

The NH_3-N concentrations ranged from 0.00 to 64.80 mg/L, with the monthly average values for the year between 24.48 and 37.10 mg/L. The average concentration of NH_3-N was the lowest in August and the highest in May. Although the overall distribution of NH_3-N data was relatively flat, the NH_3-N in rural wastewater, especially in July and August during the rainy season, still had a lower monthly average compared to the rest of the year.

The TN concentration ranged from 15.8 to 90.79 mg/L, with monthly averages throughout the year varying from 42.24 to 57.12 mg/L. August had the lowest average TN concentration, while April had the highest. The TP concentration ranged from 1.45 to 12.86 mg/L, with monthly averages ranging from 4.10 to 5.46 mg/L. August had the lowest average TP concentration, and February had the highest. Similar to COD and NH_3-N, both TN and TP concentrations were lower from June to September, with the lowest concentrations observed in August.

Overall, the concentrations of COD, NH_3-N, TN, and TP in rural wastewater in Delhi were lower from June to September. These indicators generally followed the trend of higher influent concentrations in winter and lower concentrations in summer, which was consistent with reports in several studies [14,15]. Climate and rainfall have a certain impact on water quality [16–18]. As shown in Fig. S1, the rainfall of Delhi dramatically decreased in winter, which may contribute to the concentration of domestic wastewater. Additionally, during winter, the low flow in the sewage network could lead to sediment formation in the pipes [19]. In contrast, during the summer, the rise in temperature leads to an increase in water usage by residents. Additionally, the increased summer rainfall results in more rainwater mixing into the sewage system, lowering the influent concentrations. This affects the stable operation and treatment efficiency of the wastewater treatment facilities, thereby further highlighting the importance of implementing rainwater and sewage separation measures.

3.2.2. The concentration and ratio of TN and TP

The balance of carbon, nitrogen, and phosphorus in the influent wastewater of municipal WWTPs is crucial for the effectiveness of the biological degradation process. These parameters can guide the design and configuration of the treatment system to achieve optimal nutrient removal efficiency. In order to achieve efficient wastewater treatment, it is widely recognized that BOD:N:P ratios should be between 100:10:1 and 100:5:1 for aerobic treatment [20], and 250:5:1 for anaerobic treatment [21]. High concentrations of individual substances and unfavorable nutrient ratios might reduce the degradation efficiency of microorganisms.

The influent wastewater of Delhi municipal WWTPs contained high concentrations of nutrients, mainly nitrogen and phosphorus. The concentration ratio of TN and TP in the influent water (as shown in Fig. 5), ranges from 5.70 to 21.73, with a mean of 12.45 and a median of 11.01. The cumulative probability of TN/TP in the desirable range for these plants was only 33.33%. Therefore, additional denitrification and phosphorus removal techniques are required for plants with high TN/TP ratio for further treatment of wastewater.

3.2.3. The concentration and ratio of NH_3-N and TN

Nitrogen in wastewater exists in four main forms, namely ammonia nitrogen (NH_3-N), organically bound nitrogen (organic nitrogen), nitrite nitrogen (NO_2-N) and nitrate nitrogen (NO_3-N) [22]. In the influent of WWTPs, nitrogen is usually present in the form of ammonia and organic nitrogen [23]. According to Fig. 6, the ratio of TN to NH_3-N in the influent ranged from 0.37 to 0.89, with an average value of 0.66 and a median of 0.70. Additionally, the cumulative probability of the NH_3-N/TN ratio falling within the range of 0.5–0.8 was 66.67%. NH_3-N/TN ratio generally varied between 0.17 and 0.58 [24]. This indicated the concentration of NH_3-N is a bit high, which might lead to eutrophication of the water body and the production of toxic substances. Therefore, it is recommended that the relevant wastewater treatment plants with high NH_3-N content further treat the effluent according to the Chinese National Emission Standards (GB18918-2002).

3.2.4. The concentration and ratio of COD and TN

The COD/TN ratio in the influent of municipal wastewater treatment plants is crucial for Biological Nutrient Removal (BNR) processes, as COD acts as a limiting factor for phosphorus release and denitrification, particularly for wastewater with lower COD/TN ratios [25]. Henze and Harremoes [26]suggested that a typical COD/TN ratio range of 8–12 effectively promoted denitrification or complete denitrification processes. As shown in Fig. 7, the COD/TN of WWTPs in Delhi ranged from 2.63 to 6.28, with a mean value of 5.03 and a median value of 4.46. Overall, the influent COD/TN ratio was relatively low, and an external carbon source should be added to achieve effective denitrification [27]. In practical applications, these WWTPs achieve efficient denitrification processes by adding external carbon sources such as biomass carbon sources, polyacrylamide, and methanol.

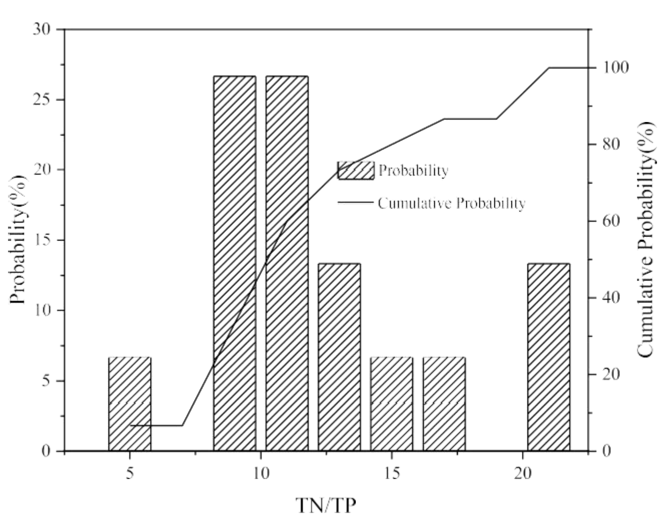

Fig. 5. Probability distribution of influent TN/TP.

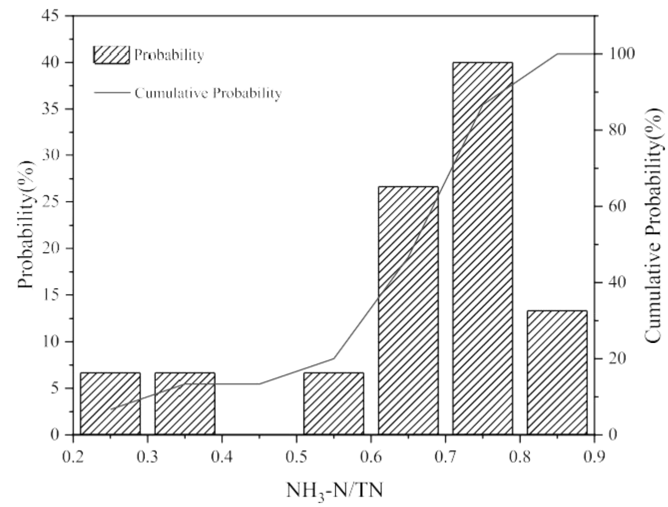

Fig. 6. Probability distribution of influent NH_3-N/TN.

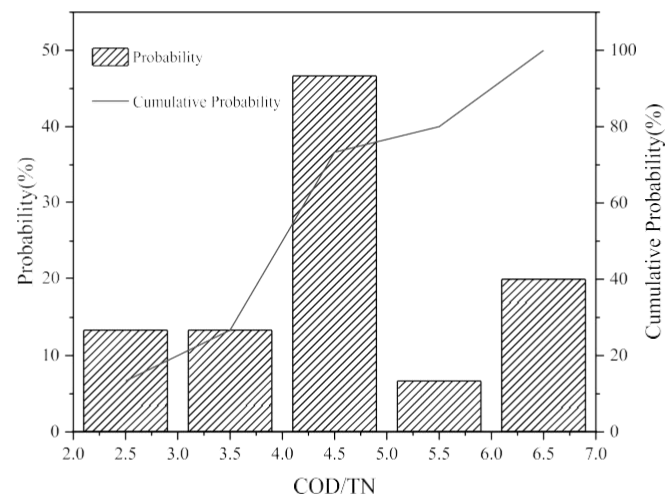

Fig. 7. Probability distribution of influent COD/TN.

3.3. Effluent water quality

Fig. 8 illustrated the removal efficiency of the main pollutants in the influent. The COD removal efficiency was consistently above 60%. The NH_3-N removal efficiency was even higher, exceeding 85% and the TP removal efficiency also reached over 75%. These indicated the high efficiency of the WWTPs in removing these pollutants. However, the removal efficiency of TN was not ideal. In some cases, its removal efficiency was even below 60%. Notably, the TN removal efficiency in the S2 plant in December was only 52.12%, which was far lower than the expected. Considering that the S2 plant adopts the AAO treatment process, the low removal efficiency may be related to the insufficient supply of organic carbon sources in the denitrification process. In the denitrification process, organic carbon sources act as essential electron donors. If the carbon source content in the wastewater is insufficient, it will directly affect the activity of denitrifying bacteria, thereby limiting the production of nitrogen gas and reducing the TN removal efficiency. To improve the TN removal efficiency, it may be necessary to further optimize the operating conditions of the AAO process to ensure an adequate supply of organic carbon sources or explore other feasible methods of supplementing carbon sources.

These 20 WWTPs have different wastewater discharge standards, including the Grade A Standard of the “Discharge Standards for

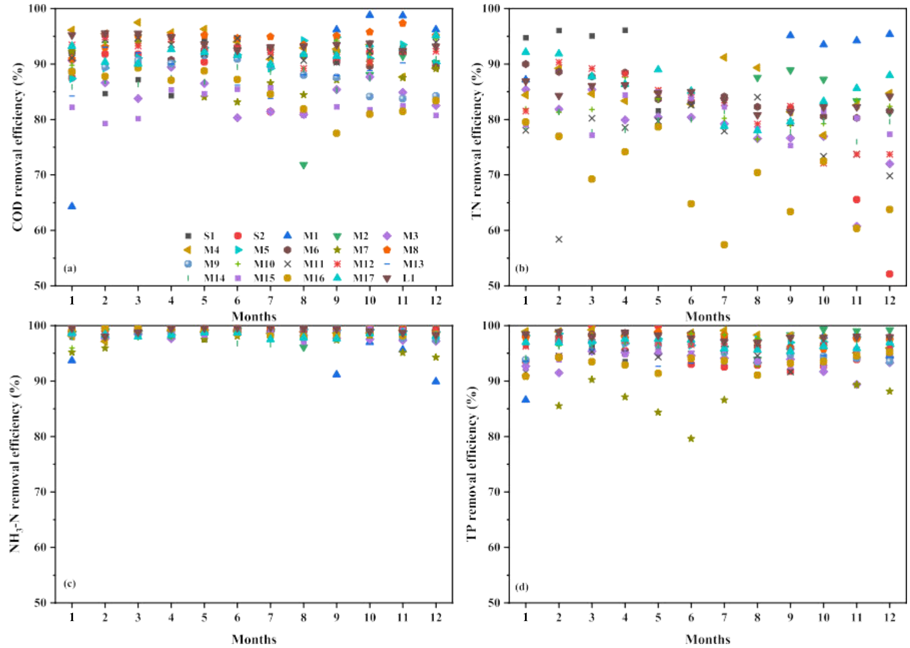

Fig. 8. The removal efficiency of the main pollutants (a)COD, (b)TN, (c)NH_3-N, (d)TP.

Municipal Wastewater Treatment Plants"(GB 18918-2002), the "Environmental Quality Standards for Surface Water"(GB 3838-2022), and the "Pollutant Discharge Standards for the Yamuna River Basin in Henan Province"(DB41/2087-2021). The discharge standards and corre- sponding pollutant concentration limits implemented by different WWTPs were summarized in Table 3. The monthly average values of the effluent water quality of WWTPs in Delhi in 2023 were shown in Fig. 9. Overall, the effluent water quality was good, and the main pollution indicators (monthly average values of pH, COD, TP, and NH_3-N) all met the discharge standards by 100%.

Table 3
Discharge standards implemented by WWTPs.

WWTPs	Standards	COD	TN	TP	NH_3-N
M1	Secondary discharge standards for water pollutants in the Yellow River Basin of Henan Province	50	15	0.5	5
L1	COD, NH_3-N, and TP: Class IV surface water standards, TN ≤ 10 mg/L,		10		
S2 M3 M5 M7 M8 M9-15 M11 M17	COD, NH_3-N, and TP: Class V surface water standards; other factors: Secondary discharge standards for water pollutants in the Yellow River Basin of Henan Province:	40	12	0.4	2
S1 M12	COD, NH_3-N, and TP: Class V surface water standards; other factors: Grade A standards for urban sewage treatment plants		10		
M2	TN: Grade A standards for urban sewage treatment plants; other factors: Class V surface water quality standards		15		
M4 M6 M10 M13 M14 M15 M16	COD, NH_3-N, and TP: Class V surface water standards; other factors: Grade A standards for urban sewage treatment plants				

4. Future potential of the reclaimed water in Delhi

4.1. Analysis of potential utilization of reclaimed water

The trend of water supply in Delhi over the past five years was clearly shown in Fig. 10. Between 2018 and 2019, the city had no wastewater reuse. However, from 2020 to 2022, although the reuse of wastewater had started, the proportion of wastewater reuse in the total water supply remained at a relatively low level, accounting for only 0.61%, 2.18%, and 1.61% respectively. The utilization rate of reclaimed water was also quite low, accounting for 5.44%, 12.22%, and 10.23% respectively. At present, only Noida District, Delhi County, have implemented wastewater reuse, with the proportions of their respective water supplies being 2.9%, 1.4%, and 1.1%. The use of reclaimed water is primarily through three pathways: agricultural irrigation, industrial reuse, and ecological water replenishment. Specifically, the WWTPs in Noida Town of the Yamuna River basin uses some of the treated water for agricultural irrigation and road cleaning; Although Gurgaon County is building a recycled water plant, it has not yet been put into operation; the Yamuna River basin has not yet established a recycled water plant or related supporting facil- ities. This indicated that the potential for the resource utilization of wastewater has not yet been fully tapped (see Fig. 11).

According to the "14th Five-Year Plan" for Ecological Environment Protection and Eco-economic Development in Delhi, the city plans to enhance the use of unconventional water sources and promote the construction of reclaimed water and rainwater reuse projects, aiming to increase the reclaimed water utilization rate to 30% by 2025. Taking 2022 as an example, if Delhi can successfully achieve this goal, it will significantly change the city's water supply structure. At present, surface water is the main source of water for landscape use, and the reuse of recycled water will greatly reduce the dependence on surface water resources, thereby achieving more sustainable water resource manage- ment. Data from the Delhi Water Resources Bulletin shows that the

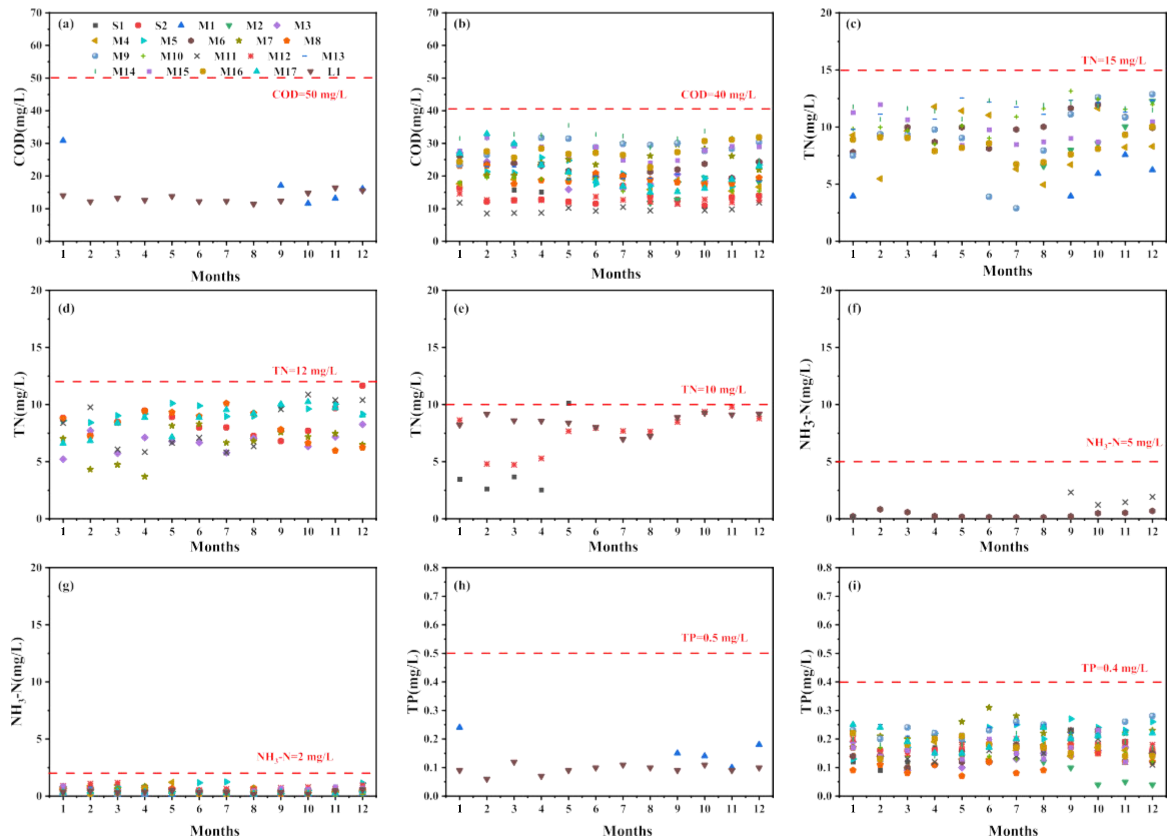

Fig. 9. Box plot of monthly variation in effluent indicators.

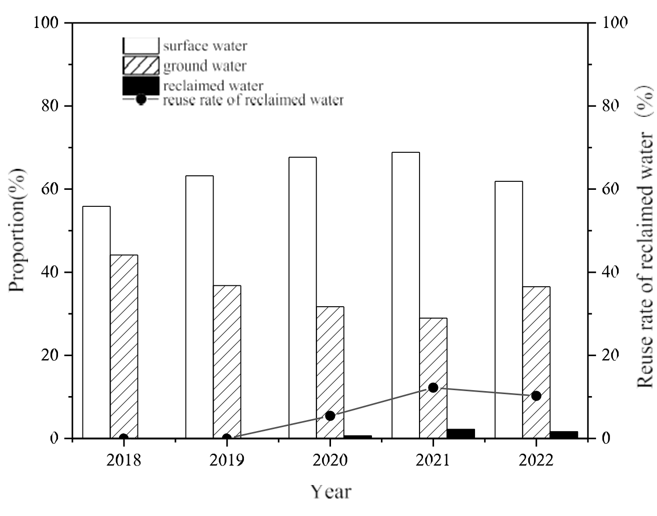

Fig. 10. Water supply source share in Delhi in the last five years.

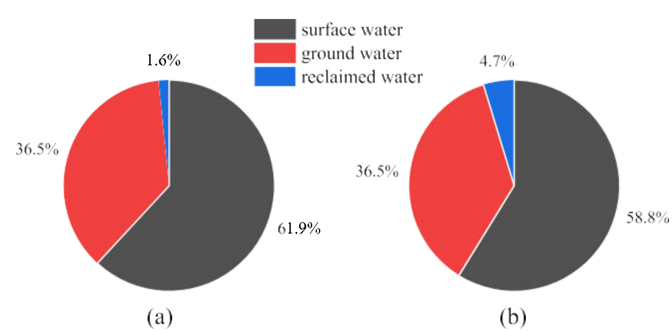

Fig. 11. Water supply source share in Delhi in2022 (a) Reality, (b) Assumption.

average comprehensive domestic water consumption per capita in urban areas was 117.8 L/day in 2020 and 126.6 L/day in 2021. Considering the water usage situation in Delhi, an average domestic water consumption of 120 L/day per capita is taken for calculation. Based on the "Urban Drainage Engineering Planning Standards" and the "Outdoor Drainage Design Standards," it is predicted that the urban domestic wastewater treatment volume in Delhi City will reach 90.57 million tons in 2025. If the planning target is achieved, with a reclaimed water utilization rate of 30%, it is estimated that the reclaimed water reuse volume in Delhi will reach 27.17 million tons by 2025.

The effluent standards of Delhi's WWTPs generally meet or exceed Class A standards, satisfying the water quality requirements for artificial wetland inflow. By planning and constructing artificial wetland tail-water purification projects in a reasonable manner, the quality of the effluent from WWTPs can be further improved to meet the water demands for ecological replenishment and other multiple uses. Water usage statistics for 2022 show that ecological water accounts for 8.4%, and the industrial water demand in industrial parks accounts for 7.6% (Fig. S3). By planning and constructing recycled water plants and their supporting pipeline facilities, Delhi can reuse treated industrial wastewater locally in industrial parks and enterprises, further optimizing the recycling of water resources.

Overall, Delhi has already established the basic conditions for recycled water reuse and possesses significant potential for recycled water utilization along with a strong demand for water. Therefore, Delhi should plan early and comprehensively to build a city-wide coordinated regional recycled water recycling system to effectively address the current water resources and water environment challenges.

4.2. Environmental impact

According to the standard system of “Classification of Urban Wastewater Reuse” (GB/T 18919-2002), the wastewater treated by municipal WWTPs in Delhi had excellent water quality. Specifically, as shown in Fig. 12, the COD in the effluent ranged between 9 and 35 mg/L, with a cumulative probability covering 3.225%–100%, fully meeting the standards of ’Water Quality for Urban Wastewater Reuse in Industrial Uses’ (GB/T 19923-2024). This indicated that the treated water was suitable for industrial production. At the same time, the TN concentration ranged between 2.5 and 13.5 mg/L, with a cumulative probability extending from 1.38% to 100%. This not only met the standards for industrial water use but also complied with the requirements of “Water Quality for Urban Wastewater Reuse in Landscape Irrigation” (GB/T 18921-2019). Notably, when the TN concentration was less than or equal to 10.0 mg/L (with a cumulative probability of 1.38%–73.27%), this indicated that the treated water was even more suitable for landscape environments with higher water quality demands. In addition, the TP concentration ranged between 0.03 and 0.31 mg/L, with a cumulative probability covering 0%–100%. This also met both the industrial water and landscape irrigation water standards. The cumulative probability of TP being ≤0.3 mg/L was as high as 99.54%, further demonstrating the suitability of the treated water for use in high-demand landscape environments. The NH_3-N concentration remained between 0.1 and 2.3 mg/L, with a cumulative probability ranging from 21.20% to 100%. This met the multiple standards of “Water Quality for Urban Wastewater Reuse in Urban Miscellaneous Uses” (GB/T 18920-2020), “Water Quality for Urban Wastewater Reuse in Landscape Irrigation” and “Water Quality for Urban Wastewater Reuse in Industrial Uses”. Therefore, this treated water was highly likely to be suitable for landscape irrigation.

However, using treated water for landscape environmental purposes also poses non-negligible risks, including health risks, the risk of algal blooms, and the risk of accumulation of toxic and harmful pollutants. Therefore, the newly constructed reclaimed water plants need to pay special attention to water quality indicators such as nitrogen and phosphorus nutrients, pathogenic microorganisms, residual chlorine, heavy metals, and toxic and harmful pollutants. The specific water quality requirements are shown in Table 4.

Statistics have shown that carbon emissions generated in the wastewater treatment process account for about 1–2% of India’s total carbon emissions [28], and it is an indispensable part of India’s carbon neutrality process. The reason for this is that the wastewater treatment process involves a large amount of energy consumption, mainly including electricity consumption and fuel consumption. Among them, electricity consumption accounts for a higher proportion [29]. Additionally, electricity costs have become one of the main costs of operating WWTPs. Electricity costs can account for more than 20% of the total costs, and in some projects with high-energy-consuming equipment, the proportion of electricity costs can reach as high as 50% [30]. The specific electricity consumption per unit of water volume (Eq. (2)) and the specific electricity consumption per unit of COD removal (Eq. (3)) for the nine wastewater treatment plants were listed in Table 5 in this study.

$$\text{Electricity consumption per unit of water} \quad \text{kW}\cdot\text{h}/ \; = \frac{\sum^{12}\text{Monthly electricity consumption}}{\sum_{1}^{12}\text{Monthly treated water quantity}} \tag{2}$$

$$\text{Electricity consumption per unit of COD removal } (\text{kW}\cdot\text{h}/\text{kg.COD}) = \frac{\sum^{12}\text{Monthly electricity consumption}}{\sum_{1}^{12}[\text{Influent COD-Effluent COD}]} \tag{3}$$

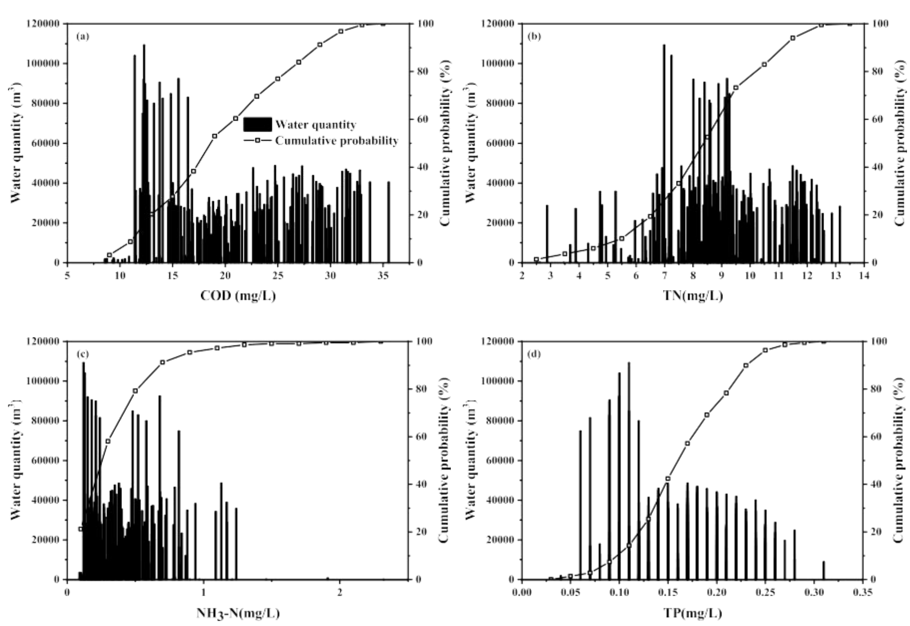

Fig. 12. Distribution of main pollutant concentrations in the effluent of Delhi WWTPs (a)COD, (b)TN, (c)NH_3-N, (d)TP.

Table 4
The reuse of urban recycling water—Water quality standard for scenic environment use.

No.	Water quality indicators	Water for ornamental landscape environments			Water for recreational landscape environments			Landscape wetlands environmental water
		River classes	Lake classes	Waterscape classes	River classes	Lake classes	Waterscape classes	
1	Basic requirement	No floating matter, no unpleasant smell or taste						
2	pH	6.0–9.0						
3	BOD_5/(mg/L)	≤10	≤6		≤10	≤6		≤10
4	Turbidity/NTU	≤10	≤5		≤10	≤5		≤10
5	TP/(mg/L)	≤0.5	≤0.3		≤0.5	≤0.3		≤0.5
6	TN/(mg/L)	≤15	≤10		≤15	≤10		≤15
7	NH_3-N/(mg/L)	≤5	≤3		≤5	≤3		≤5
8	Fecal coliform bacteria/ (number/L)	≤1000			≤1000		≤3	≤1000
9	Residual chlorine/(mg/L)	–					0.05–0.1	–
10	Chroma/degree	≤20						

Table 5
Electricity consumption of municipal WWTPs in Delhi.

WWTPs	Scales	Electricity consumption per unit of water (kW·h/m^3)	Electricity consumption per unit of COD removal (kW·h/ kgCOD)
M4	2	0.55	1.81
M5	2.5	0.42	1.71
M7	3	0.58	3.39
M8	3	0.39	1.18
M13	5	0.36	1.90
M14	5	0.58	4.14
M15	5	0.45	3.38
M16	5	0.41	2.80
M17	5	0.31	1.22

Compared to the national median values for electricity consumption in municipal WWTPs in 2020, which were 0.36 kW h/m³ for water volume and 2.14 kW h/kg COD for COD removal [4], the operational energy consumption of the wastewater treatment plant in Delhi was relatively high, resulting in greater costs. In the future development and utilization of reclaimed water in Delhi, the cost of electricity consumption needs to be specially considered.

4.3. Social and economical impacts

From the perspective of social impact, the construction and operation of reclaimed water projects will provide numerous job opportunities for society. Additionally, the use of reclaimed water will improve the water environment, leading to a more livable and pleasant living environment for people.

From the perspective of economic impact, the current tiered water price in Delhi is 0.36 \$/m^3. In Beijing, where reclaimed water technology was first implemented, the price of reclaimed water is about 0.49 \$/m^3. This indicates that reclaimed water has a relatively high economic benefit. Additionally, comparing the household costs of unconventional water sources in Beijing (reclaimed water, South-to-North Water Diversion, and seawater desalination) for 2016 [4], the cost of recycled water is 0.42 \$/m^3, South-to-North Water Diversion is 1.11 \$/m^3, and seawater desalination ranges from 1.26 to 1.41 \$/m^3. Among these unconventional water sources, recycled water offers a cost advantage.

4.4. Existing challenges

Conducting water reuse on a larger scale possesses advantages such as enhanced water security, economic benefits and Environmental sustainability. At present, Delhi encounters a range of challenges in advancing the utilization of reclaimed water. The primary concern is that the city's policy and regulatory framework for reclaimed water utilization is incomplete, lacking essential mandatory stipulations and detailed management protocols. This results in an evident insufficiency in the capacity for managing reclaimed water. Furthermore, Delhi is in the nascent phase of water quality monitoring, early warning, and emergency response, having not yet developed an effective emergency management system and strategic responses, thus augmenting the potential safety hazards in the utilization process of reclaimed water.

What's more, there is an urgent need to optimize the planning and layout of reclaimed water utilization in Delhi. Currently, the city's methods for reusing reclaimed water are rather limited and lack systematic and holistic planning directives, leading to an imbalance between the supply and demand for reclaimed water. The utilization of reclaimed water predominantly involves small-scale and short-term processes, failing to implement an efficient model of "prioritizing high-quality water use, differentiating water quality, and cascading water recycling". This restricts the optimization of reclaimed water resources. Lastly, the development of the reclaimed water distribution system requires further enhancement. Delhi has constructed only one reclaimed water plant, which remains non-operational. It is also deficient in the necessary supporting pipelines and storage facilities, severely constraining the potential applications of reclaimed water. Moreover, the city's wetland parks have not been effectively tapping into the effluent from wastewater treatment plants, further highlighting the deficiencies in infrastructure and system construction.

5. Conclusions

This study evaluates the potential and challenges of reclaimed water utilization in Delhi, a lower-middle income city in India facing severe water scarcity. Based on the analysis of data from 20 municipal WWTPs in 2023, major conclusions are as follows.

Most WWTPs use the AAO process for biological treatment. Seasonal variability in hydraulic load rates, especially during the rainy season, poses operational challenges, with some plants exceeding capacity limits. This indicates a need for infrastructure upgrades and improved rainwater management. Influent water shows high levels of COD, NH_3-N, TN, and TP, with nutrient ratios often surpassing optimal levels for biological nutrient removal. While effluent quality meets national standards, TN removal efficiency is suboptimal, necessitating enhanced denitrification processes.

Delhi has significant potential to increase reclaimed water utilization to 27.17 million tons by 2025, achieving a 30% utilization rate. Treated water meets industrial and landscape irrigation standards, reducing reliance on surface water and promoting ecological sustainability. Implementing artificial wetlands and advanced purification processes is essential to mitigate risks like eutrophication and pollutant accumulation.

Expanding reclaimed water projects offers social benefits due to cost-effective water reuse. Reclaimed water is more economical compared to other unconventional sources like seawater desalination, reinforcing its viability as a sustainable water management strategy. Despite the potential, challenges include inadequate regulatory frameworks, fragmented planning, and limited infrastructure for large-scale reuse. Addressing these issues requires developing robust policies, systematic planning, and investing in advanced treatment technologies. Integrating reclaimed water with rainwater management can provide a resilient solution to Delhi's water scarcity.

In summary, reclaimed water utilization offers a viable pathway to alleviate water scarcity in Delhi, supporting both economic growth and environmental sustainability. Coordinated efforts in policy development, infrastructure expansion, and technological innovation are essential to achieve a secure and sustainable water future for the city.

CRediT authorship contribution statement

V Ramanjaneyulu: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **A Rajasekar Babu:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization..

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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