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Application of UF and RO for power plant's wastewater treatment and recycling for environmental sustainability

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ABSTRACT

Global indicators have warned of freshwater scarcity in Asia. However, the utilization of freshwater resources has skyrocketed for commercial and industrial purposes without any strategy for recycling and reuse. The power plant's wastewater/reject mainly consisted of cooling tower blowdown water and reverse osmosis (RO) plant reject water. Due to the high turbid nature of reject water, pretreatment was carried out to achieve $SDI_{15} < 3$ by employing multimedia filters (MMF), activated carbon filters (ACF) and ultrafiltration (UF). Operational parameters of RO membranes were optimized (11.5 bar, 29 °C) to achieve maximum water recovery along with higher rejection rates of critical scale forming species such as 81% total dissolved solids (TDS), 73% calcium hardness and 72% silica (Si). After accounting for backwash water and other concentrate rejections, the membrane treatment plant has achieved an appreciable recovery rate of more than 44%. The RO membrane-treated water was then incorporated in the cooling tower and a 16% reduction in freshwater makeup was achieved. Reduction of microbial growth rate as well as corrosion and scaling in the cooling tower was observed due to the reuse of treated water. This is to confirm here that brackish water RO membranes can act as a strong contender for reject water reclamation and effective utilization.

Key words: brackish water RO membrane, environmental sustainability, power plant, wastewater treatment, water reclamation

HIGHLIGHTS

- Lower TDS Brackish Water Reverse Osmosis (BWRO) membranes are found effective for recovery of high TDS wastewater of cooling tower.
- Significant expulsion of turbidity and suspended particles was achieved through contemporary technologies, i.e., ultrafiltration (UF) and multimedia filters (MF).
- Pretreatment plays an important role in the operational life span of RO membranes.
- Membrane treatment of wastewater provided a recovery rate of more than 40%.
- Wastewater recycling and reuse suppressed the utilization of freshwater and chemical consumption in the cooling tower.

1. INTRODUCTION

Water is a vital need for life and an essential component for ecological sustainability. According to the Institute for Water, Environment and Health survey, less than 3% of Earth's water reserves exist as freshwater, whereas 30% of the freshwater is present in the form of groundwater (Guppy & Anderson 2017). Exponential population growth, massive urbanization and industrialization are threatening toward the acute scarcity of usable water. Due to inappropriate infrastructure and lesser resources, the issue of the availability of water resources is intense in developing countries. In these regions, there is no systematic and effective policy to conserve vital resources. Large differences between water utilization and its availability have led to further adverse environmental and economic concerns. According to the United Nations Development Program (UNDP) report, every continent will face water shortage, as one-fifth of the global population is already facing water scarcity (UNESCO 2019) (Bond *et al.* 2019). The World Economic Forum has also drawn global attention to water shortage by ranking water scarcity as an inevitable and influential risk (WEF 2016). Water scarcity has been ranked on the top of the most

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notorious global issues such as lethal weapons, food availability, diseases and cyber issues. Nowadays, water scarcity has retarded the availability of freshwater sources for general and industrial utilization. Major industrial sectors comprised of thermoelectric power plants, petrochemical industries, sugar industries, refineries and textile industries are the major consumers of water at a larger extent.

The process of transforming wastewater from diverse sources and processing it into usable for another purpose is known as reusing water. However, for all sources including domestic, municipal or industrial, wastewater can be recycled and, depending on its quality, it can be used for a number of secondary applications. Examples of secondary uses include irrigation for agriculture, groundwater recharge, industrial processes, potable water delivery and non-potable urban applications. Since reused water is a dependable source during the present time of freshwater scarcity, it is being used more frequently for agricultural irrigation. The use of nutrient-rich treated wastewater for agriculture may also increase output, reduce (or eliminate) the need for fertilizer application and promote food security. Utilizing treated wastewater in place of groundwater for irrigation can help conserve water. Another region where treated wastewater can serve such requirements is the cooling in industrial processes.

Wastewater being comprised of blowdown water or reject water from power plant's wet-type recirculating cooling tower is a major concern for water sustainability. For optimum operation of the cooling tower and condenser, a part of the water is rejected on purpose termed as cooling tower blowdown (CTBD). Apart from the application of chemical treatment, blowdown is still carried out when the solid load increases in concentrated cooling water. In comparison with other reject water sources, blowdown water from a power plant's cooling tower, usually containing scale, corrosion and biofouling inhibitors, can be recycled, and reused again in the cooling tower, after it is sufficiently treated to remove these (Mahir *et al.* 2021).

CTBD water generally contains diverse constituents such as total dissolved solids (TDS), total suspended solids (TSS), turbidity, chlorides, silica, calcium and magnesium hardness and organic and inorganic contamination (chemical oxidation demand, COD/biological oxidation demand, BOD) in higher concentrations and these vary from plant-to-plant scenario. Considering blowdown water's constituents' nature and range, various conventional and non-conventional technologies have been employed for pretreatment and principle treatment (Maqbool *et al.* 2019). If water possesses high turbidity, COD or BOD demand in case of organic and inorganic contaminations, divalent and trivalent ions coagulation and filtration pretreatment techniques are generally employed. To remove aromatic contents, chlorine residuals, oil and greases, an activated carbon pretreatment system is utilized (Ahmed *et al.* 2020; Shukla *et al.* 2020). The side stream filtration technique is commonly utilized for in-line cooling water treatment to minimize scaling issues and water consumption. Wang *et al.* (2014) studied the effect of four different coagulants pretreatment over blowdown water, which was subsequently treated by reverse osmosis (RO) membrane. For 23-hour pilot plant operation, the influent pollutants such as turbidity, TDS, COD and total iron contents decrease at the dosage rate of 20 and 15 mg/L of cationic polyacrylamide and polyaluminum chloride, respectively, thus, transforming the polluted water into a condition ($\mathrm{SDI} < 5$) to enable being treated by RO membrane for reuse. Altman *et al.* (2012) conducted a pilot scale study by employing nanofiltration (NF) membrane as a side stream filtration technique. The NF permeate was returned to the cooling tower and the NF concentrate discharge was discarded into the sewer. According to this study, an appreciable reduction in blowdown water was achieved by the NF membrane. However, silica scaling has hindered further recovery. Davood Abadi Farahani *et al.* (2016) investigated and evaluated two types of pretreatment techniques for final NF and RO membrane treatment, to carry out effective CTBD treatment and conservation. However, promising results have been depicted by coagulation–flocculation and ultrafiltration pretreatment for RO treatment than the pretreatment carried out for NF membrane.

On a laboratory scale or lower, conventional technologies such as coagulation, flocculation, softeners, adsorption and biological treatment are promising. But on a commercial scale, these technologies lose their productivity and efficiencies as they require a higher amount of specific coagulant or adsorption material as well as needing a large installation area and proper decomposition of aided chemical/physical materials (Löwenberg & Wintgens 2017; Soliman *et al.* 2022). From a careful scrutiny of literature, it can be established that the contemporary membrane technology integrated with pretreatment filters has been found superior to conventional pretreatment options on a commercial scale (Löwenberg *et al.* 2015; Koeman-Stein *et al.* 2016; Obotey Ezugbe & Rathilal 2020; Yang *et al.* 2020). The membrane technology is a compact treatment regime as it requires less installation area and is effective for a wide range of pollutants removals such as silts, TDS, hardness, silica and phosphate and easy control over the operation.

Raji & Packialakshmi (2022) presented a soil matrix technique for the elimination of contaminants from wastewater effluents. Three types of sands were utilized such as fine, loamy and clayey to assess the change in pH and removal of TDS and turbidity. The team observed a significant reduction in pH from 8.5 to 7.5, TDS from ~1,600 to 850 mg/L and turbidity from 7.3 to 4 NTU. It was found that the soil-based technique was effective in improving effluent quality for groundwater recharge.

Scharnberg *et al.* (2020) established the synthesis of novel photocatalysts $Bi_2Fe_xNbO_7$ by the sol-gel method. The team found that with iron addition, the photocatalyst $Bi_2Fe_xNbO_7$ had higher absorption and a smaller band gap energy of 2.09 eV. The addition of iron also resulted in an enhanced crystallinity. The Bi–Fe–Nb–O powder was also found to be stable and reusable and had potential as effective photocatalysts for environmental applications such as used for pretreatment systems for principle technology.

The current study was conducted on a recirculating induced draft cooling tower of a 16 Mega Watt (MW) waste heat recovery power plant at one of the plant sites of Bestway Cement Ltd (United Kingdom Group), Pakistan. Due to the dusty environment of cement industry, the process water is prone to high turbidity. The makeup water source for the cooling tower is underground water (brackish water). The cooling tower's designed recirculation rate is 4,000 m^3/h, whereas the sump volume is 1,350 m^3. However, operational recirculation rate varies from 3,000 to 3,500 m^3/h. The blowdown water from cooling tower is collected in a drain pit. For the optimal process, TDS contained by sump cooling water is maintained at ~1,500 mg/L. To overcome the problems including scaling, corrosion, slime, algae formation and biofouling, phosphonate and sulfonate-based scale inhibitors, zinc salt and phosphonic acid corrosion inhibitor, isothiazolinone-based biocide and non-ionic biodispersant are dosed. For aerobic microorganisms, sodium hypochlorite (NaOCl) is utilized, and free chlorine residuals are maintained between 0.1 and 0.5 ppm. For better working of specialized chemicals and cooling tower system performance, pH is maintained in the range of 7.8–8.3 by commercial grade sulfuric acid (H_2SO_4), while calcium hardness is kept in the range of 750–900 mg/L.

The primary focus of this study is to determine the effectiveness of lower TDS brackish water RO membranes for wastewater/reject treatment for water recovery (conservation) from two main reject sources such as CTBD water and RO plant concentrate/reject water. A wastewater/reject treatment plant, specifically aimed to treat rejected water sources, integrated with brackish water RO membranes, was fabricated from a local manufacturer for water recycle and reuse into the cooling tower for better water conservation and system sustainability. Influence of various parameters of pretreated water on RO membrane was determined with special attention to calcium and silica scaling. Effects of the post-treatment (i.e., after water recycling to cooling tower) on the cooling tower were obtained by evaluating microbial count, scale and corrosion coupon analysis. In times of water scarcity, specifically, water reuse can serve as a dependable source of water to control demand by generating more efficient use of available resources. In addition to saving money, this measure can reduce the quantity of water that needs to be treated and used. Water reuse is an effective way to protect and enhance efforts to restore aquatic ecosystems like wetlands, streams and ponds.

2. MATERIALS AND METHODS

Laboratory grade HCl solution was procured from Sigma-Aldrich Ltd for the preparation of 5% HCl solution. Deionized water (TDS $<$ 1 mg/L) was obtained from electrodeionization (EDI) equipment. Parameters, such as pH and electrical conductivity measurements, were carried out by Trans Instruments pH and conductivity meters. TDS was determined by using a factor, 0.65 multiplied by electrical conductivity of specific sample in accordance with the APHA (2012) 2,510 (A) (Rice & Bridgewater 2012). Turbidity, total hardness and calcium hardness were analyzed by the EDTA titrimetric method in accordance with the APHA (2012) 2,340 (C) and 3500-Ca (B) (Rice & Bridgewater 2012), whereas magnesium hardness was calculated by the difference between total hardness and calcium hardness and total alkalinity or methyl alkalinity was analyzed by titration as instructed by APHA (2012) 2,320 (B) (Rice & Bridgewater 2012). Chloride and silica were measured by DR-3,900 vis-spectrophotometer by HACH Ltd. In the determination of total viable count (i.e., microbial growth rate) or bacterial count in the cooling tower, dip slide tests as part of Envirocheck TVC Merck-Millipore were performed on a weekly basis. A 45-day corrosion and scaling analysis test was performed by employing mild steel and copper coupons procured from a local supplier. Techniques and computations based on well-established methods (Löwenberg *et al.* 2015; Löwenberg & Wintgens 2017; Soliman *et al.* 2022) were employed to estimate corrosion and scaling parameters.

Silt density index (SDI_{15}) was estimated to analyze the effectiveness of pretreatment technologies to remove fouling agents which lower RO membranes performance. The silt density index (SDI_{15}) is a widely used parameter to elucidate the fouling potential of feed water across RO membrane. Feed water after each pretreatment was circulated through a 0.45 μm cellulose acetate filter at a fixed line pressure of 30 Psi (0.2 MPa). Initially, 0.5 L of filtered water (permeate water) was collected at time

t_o, and for 15 min referred to as time, T the filtered water was rejected. After 15 min, 0.5 L of filtered water was taken at time t_{15}. SDI was determined on a weekly basis and the SDI_{15} is estimated by the following relation:

$$\mathrm{SDI}_{15} = \frac{\left[1 - \frac{t_o}{t_{15}}\right] * 100}{T} \tag{1}$$

The permeate recovery (P_R) in percentage (or product water) from the membrane can be estimated from the following relation:

$$P_R\ (\%) = \frac{P_f}{F_f} \times\ 100\% \tag{2}$$

where P_f is the permeate volumetric flowrate (m^3/h) and F_f is the feed volumetric flowrate (m^3/h). To maintain a specific limit of TDS and other constituents in the cooling water, continuous and periodic discharge of recirculating water is carried out to control cycles of concentration (COC) keeping in view the threshold limit of conditioning chemicals, i.e., anti-scalants and anti-corrosion chemicals. COC depicts the accretion of TDS and other constituents as an aftermath of makeup water with leftover TDS owing to the evaporative losses, using the following relation:

$$\mathrm{COC} = \frac{\text{TDS in blowdown water (mg/L)}}{\text{TDS in makeup water (mg/L)}} \tag{3}$$

3. RESULTS AND DISCUSSION

An illustration of water-steam cycle of the power plant along with the CTBD and typical RO reject recycle water treatment plant is depicted in Figure 1. The critical parameters of reject water before undergoing any treatment and underground raw water can be seen in Table 1. A filter feed water pump withdraws water from the pit and feeds it initially to a degasifier for removal of any gaseous contents such as carbon dioxide and residual chlorine. Before degasification, sodium hypochlorite was injected to remove any biological entity by maintaining chlorine residuals at ~0.1 ppm. Subsequent to this, water was fed into the bMMF containing beds of sand, anthracite and gravels for retaining suspended particles and turbidity. After MMF, feed water passed through an ACF, which consisted of anthracite and gravel for the removal of oil, greases and any residual chlorine. Once sufficient pretreatment was carried out, water was treated by the Hydranautics manufactured ultrafiltration (UF) membrane. It removed turbidity and suspended solids and other microorganisms to prevent RO membranes from scaling and fouling, by achieving an SDI of less than 3. The UF effluents after passing through cartridge filters (pore size ~1 μm) were subjected to treatment by Hydranautic manufactured RO membranes, which underwent dosing of anti-scalants and pH adjustment chemicals. The final product of RO fed to the cooling tower operation as it contained lowered dissolved solids and no turbidity. The concentrate streams from RO membranes were collected in a tank. The backwash of MMF and ACF was carried out by the RO concentrate. The water after backwashing was collected in pits for further end usage of quarry development and plant irrigation. Dip slide tests associated with the periodic analysis of microorganisms and coupon tests for corrosion and scale analysis were also performed to predict the post-effects of treated reject water on cooling tower performance.

Pretreatment of feed water plays a critical role in RO membranes performance. Figure 2 shows the comparison of turbidity removal potential among the application of MMF, ACF and UF into the feed water. The reject water had a maximum turbidity of more than 20 NTU. The turbidity owes to the presence of particulate matter which hinders the light passage through the water. Turbidity can be considered as a visual assessment of particulate, silts, clay, dirt, biological entities, metallic oxides, oil and grease loading of reject water which cause haziness and color change. Biocide dosages were also maintained before MMF and ACF for the disinfection of feed water; however, no coagulants or flocculants were dosed prior to media filtration. As depicted by the trend, the MMF and ACF filtrate turbidity are found to be 5 NTU on an average basis. The turbidity rejection percentage of the MMF was found to be 70–80%. Since the SDI_{15} of the MMF and ACF was greater than 5, this proved in prohibiting any of these two to be used directly as RO membrane feed water. UF filtration treatment was found crucial after the disinfected water passing through MMF and ACF treatments. As shown by the UF filtrate trend, the turbidity was found to be less than 1 NTU. The UF feed water turbidity fluctuations did not affect the UF filtrate turbidity as much. The turbidity

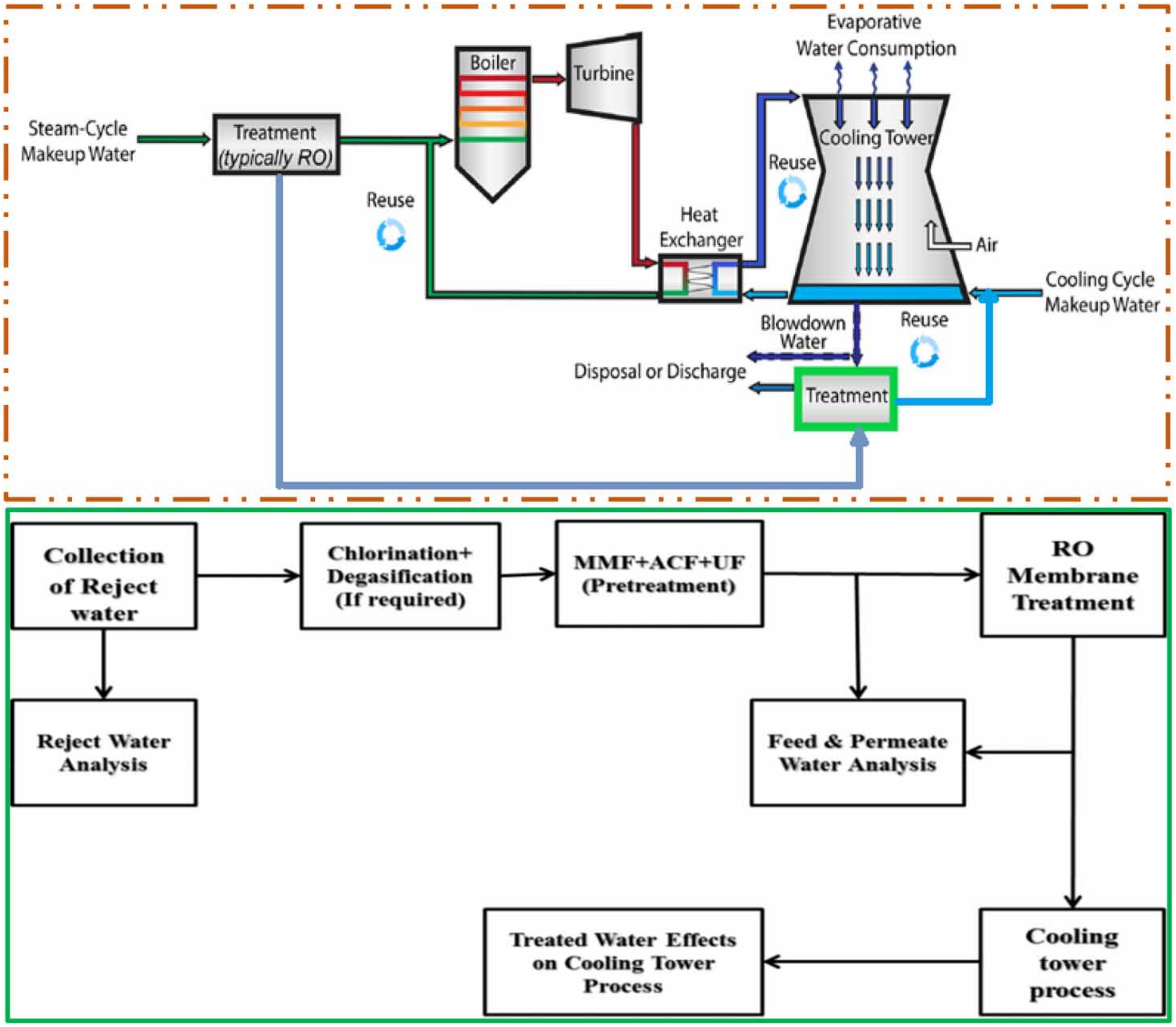

Figure 1 | Schematic of power plant's water-steam cycle and wastewater treatment block flow diagram.

rejection rate of UF is more than 90%. The results are in accordance with the findings of a case study carried out by Chew *et al.* (2016) where UF filtrate turbidity was below 1 NTU.

Pretreatment of water is vital because it helps to lower the scaling, fouling and clogging issues and provides appreciable feed quality for RO membranes. In order to determine the weather, the pretreatment for used RO membranes is effectively lowering the fouling agents, SDI tests have been performed as shown in Figure 3. The Hydranautic membrane manufacturer recommends a maximum value of 4–5 SDI_{15} for RO membrane feed water (Hydranautics 2021a, 2021b). The figure depicts that the initial SDI_{15} associated with MMF and ACF filtrate was found to be greater than 5. This figure also shows that MMF and ACF filtrate is not good to be used as RO membrane feed water as it will cause fouling of membranes. To overcome this issue, UF filtration was carried out after MMF and ACF filtration. The SDI_{15} of UF filtrate was found less than 3. From these trends, it can be seen that with the passage of time, the SDI_{15} of the MMF, ACF and UF has been slightly increased. This shows that the filtration media of MMF and ACF also retained suspended and colloidal particulates including sand and gravel. Anthracite structure was found to slowly deteriorate with the passage of time. On the other hand, the hollow fiber configuration of UF was useful to retain the remaining particulates from the filtrates of MMF and ACF. However, the monthly SDI_{15} trend of the UF indicated a value of less than 3. It was observed that the heavily fluctuated turbidity

Table 1 | Reject water streams (wastewater) and fresh/raw (underground) water analysis

			Waste/Reject water streams			
Parameter	**Units**	**Equipment/Method**	**CTBD**	**RO reject**	**CTBD + RO reject**	**Fresh/raw water**
pH		pH meter	8.31	7.46	7.8	7.27
Conductivity	μS/cm	Conductivity meter	2302.2	2015.4	–	675.4
TDS	mg/L	Conductivity meter	1496.38	1310	1484.8	440
Total alkalinity	mg/L as $CaCO_3$	Titration	157.5	155	156.1	280
Total hardness	mg/L as $CaCO_3$	Titration	1238	1080	1230	303.75
Calcium hardness	mg/L as $CaCO_3$	Titration	890	635	881	196.26
Magnesium hardness	mg/L as $CaCO_3$	Titration	348	445	359.1	107.5
TSS	mg/L	Spectrophotometer	39.1	2	38.4	<1
Chlorides	mg/L as Cl	Spectrophotometer	93.5	51.03	92.58	5.25
Silica	mg/L as SiO_2	Spectrophotometer	65.2	162	68.4	15.75
Turbidity	NTU	Nephelometer	18.1	0.9	17.1	<1

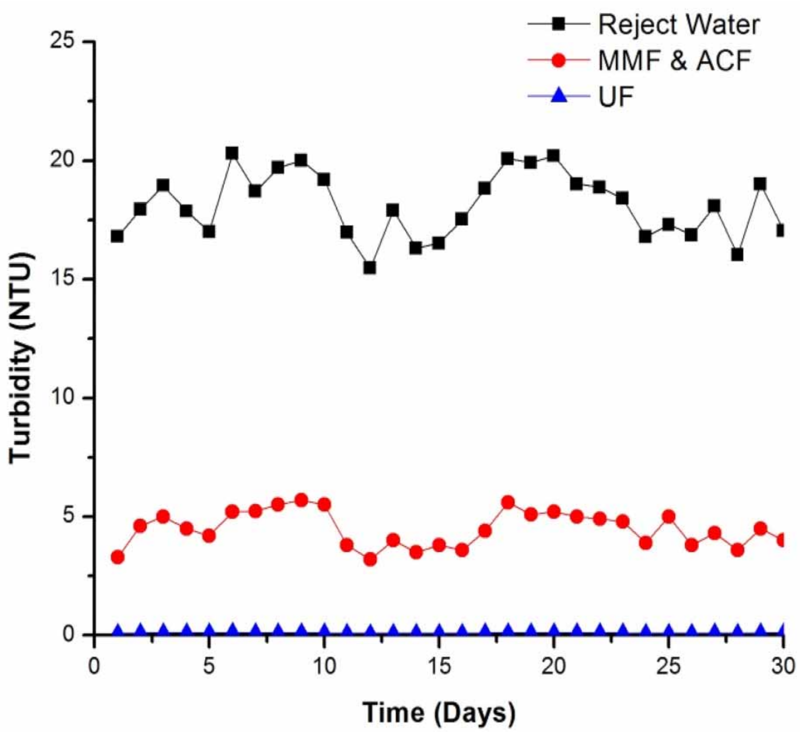

Figure 2 | Turbidity rejection of MMF, ACF and UF.

of feed water for media filtration and ultrafiltration did not appreciably affect the SDI values as the trend was smooth. This shows that SDI was unable to correlate properly between the feed conditions, membrane resistance (quantity) and total colloidal or suspended particles. The variables, affecting the integrity of SDI relation (Equation (1)), can be morphology and the sizes of particles, temperature and pressure, and pores size of the filter, this validates the assumptions due to Hossein Fayaz *et al.* (2019).

After achieving appreciable RO feed water quality, critical operational parameter of the RO membrane such as feed pressure was evaluated and optimized. On the other hand, as the temperature was governed by atmospheric conditions,

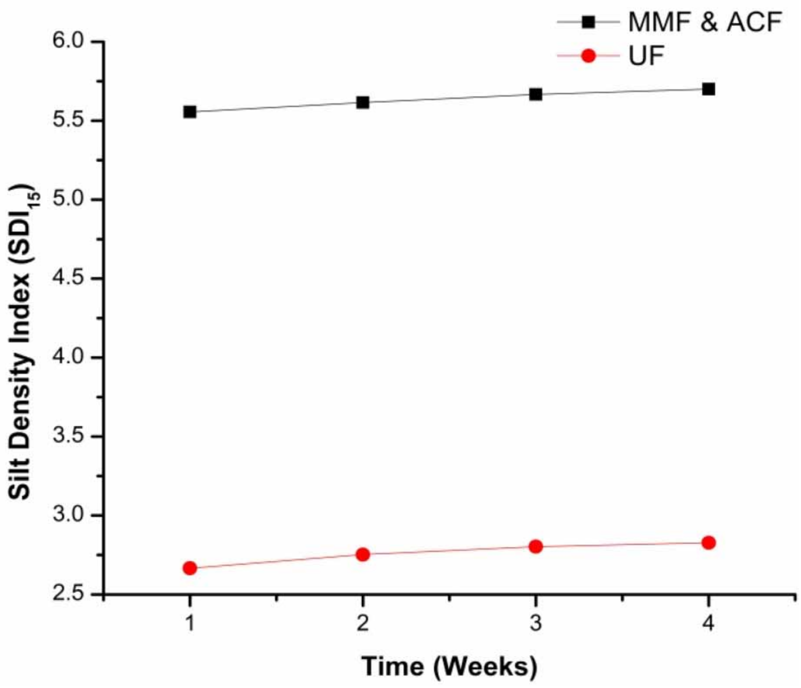

Figure 3 | SDI15 of MMF, ACF and UF vs time.

various attempts were made to establish a relation of feed temperature with the RO membrane flux by taking Equations (3) and (4) into consideration:

$$\mathrm{TCF} = \ \mathrm{Exp}\left[K*\left(\frac{1}{273+\ t}\right) - \left(\frac{1}{298}\right)\right] \tag{4}$$

where TCF is the temperature correction factor; K is the membrane constant supplied by manufacturer ($1/K = 2{,}700$); t is the temperature at operating conditions (°C). Normalized flux is given as:

$$F_{25} = F_t * \mathrm{TCF} \tag{5}$$

F_{25} is the normalized permeate flux by taking TCF into consideration at 25 °C (L/m^2 h); F_t is the actual permeate flux operating temperature (L/m^2 h).

RO membrane feed pressure was varied from 8 to 13.5 bar, to achieve optimum values for permeate (RO membrane product) recovery rate and rejection of TDS along with other scale-forming solids. As seen in Figure 4, initially the feed water pressure was set as 8 bar, and the PR rate was low at the specific rejection rate of TDS, calcium hardness and SiO_2. The figure also shows that with an increase in the feed pressure, the PR also increases simultaneously, whereas the solids rejection rate decreased slightly because of the accumulation of salts on the membrane surface and this causes accumulation of the free cavities or space into the membrane. At 13.5 bar feed pressure, the maximum permeates recovery rate of 80.5% was achieved but the rejection rate of the TDS, calcium hardness and silica was found as 77.5, 67.7 and 52.9%, respectively. However, at the optimum feed pressure of 11.5 bar, the PR of 76% was observed and the rejection rate of the TDS, calcium hardness and silica was found as 81, 73 and 72.5%, respectively. The finding of optimum feed pressure of 11.5 bar is in accordance with the findings of Chimeng (2014) (12 bar). The environmental burdens of reject water generation from industrially managed brackish water desalination plants can be reduced by optimizing the configuration of the membrane processes, which consumes relatively less energy than thermal desalination processes, to effectively recover maximum freshwater. In landlocked places, deep well injection or evaporation ponds can be used to dispose of the 20–30% of reject water produced by hybrid systems.

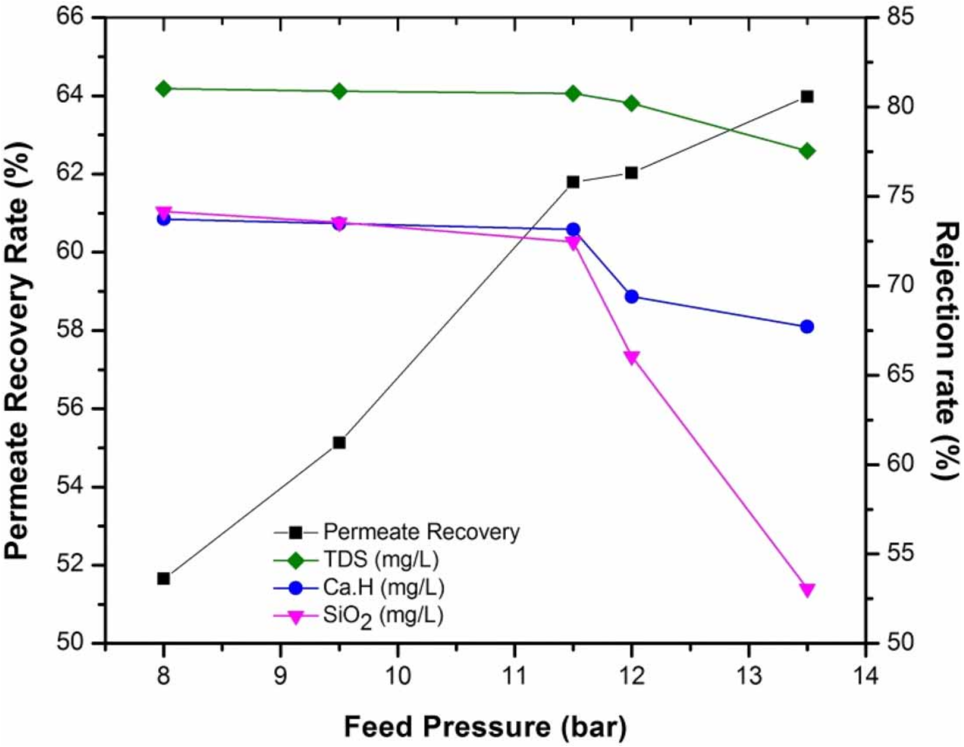

Figure 4 | Effect of feed pressure on permeate recovery and salt rejection rate.

The effect of various feed pressures on membrane flux along with rejection rates of TDS, calcium hardness and silica was also evaluated. Membrane flux represents the flow rate of permeate from the surface area of the membrane in a unit of time. Due to the direct relation between feed pressure and membrane flux, the membrane flux increased when the feed pressure was increased. Initially, no significant change in salt rejection was noted but as the feed pressure increased at maximum, the salt rejection also decreased. On the other hand, recovery rate increased with increasing feed pressure. Figure 5 depicts the effect of varying feed pressures on membrane flux along with salt rejection. The results validated the findings of Chimeng (2014).

The effect of temperature on membrane flux has also been evaluated as demonstrated in Figure 6. With an increase in feed temperature, the membrane flux increased. Figure 6 shows that the increment in the membrane is found to be linear with feed temperature. With increasing feed temperature, the viscosity of water decreased and the diffusion rate of water coming out of the membrane increased. However, the rejection rate of salts also decreased. For the sake of flow normalization, variation in membrane flux due to the feed temperature can be illustrated by the temperature correction factor, which takes into account the actual feed temperature, reference temperature (i.e., 25 °C) and membrane-specific permeability factor (Equations (4) and (5)). The optimum feed temperature range was observed within 28–29 °C. Shigidi *et al.* (2022) evaluated the impact of temperature on properties of commercially available brackish water RO membrane (BW30XFR) for the chromium-loaded wastewater treatment. They found out that by varying temperature from 25 to 55 °C at constant pressure and feed flow, there was more than a 150% increase in permeate flux. Interestingly with increasing temperatures, the lower feed flow rates have provided higher permeate fluxes as compared to higher feed flow rates. Contrarily, increasing the feed flow rates at constant temperature depicted no appreciable variations in permeate flux.

Generally, to control the operational parameters of RO membranes, two inherent modes are to be critically considered such as membrane flux and transmembrane pressures. Figure 7 presents the influence of transmembrane pressure (TMP) on the membrane flux and at constant feed pressure of 11.5 bar. To overcome the osmotic pressure of the membrane, TMP is the net driving force to initiate the separation of salts through the membrane. The varying salts concentration across the RO membranes results in osmotic pressure. However, to overcome the osmotic pressure of the RO membrane,

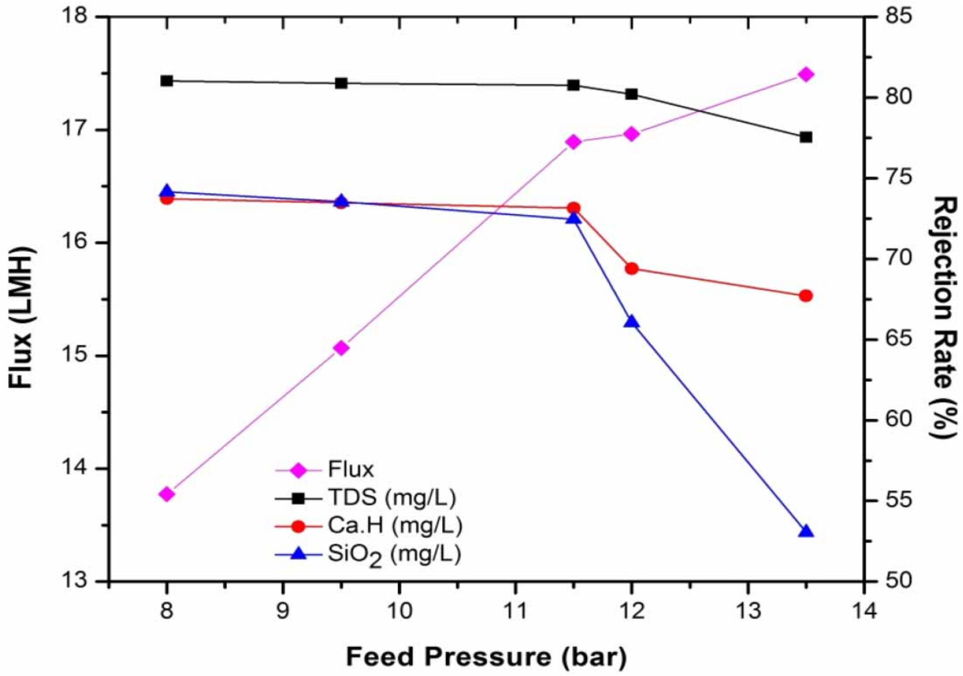

Figure 5 | Effect of feed pressure on membrane flux and salt rejection rates.

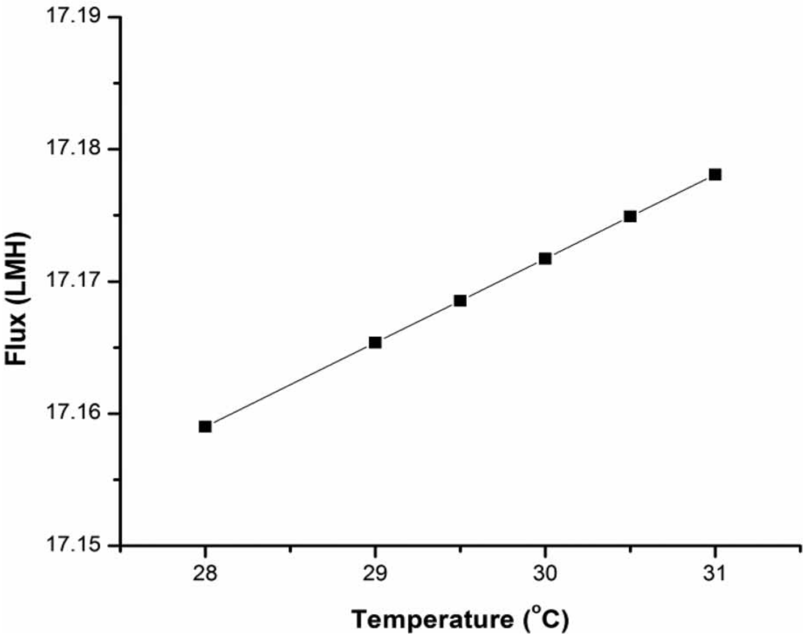

Figure 6 | Effect of feed temperature on membrane flux.

the RO feed water pumps must generate enough pressure to overcome the osmotic pressure. According to Hydranautics (2021b), a feed of 1,000 TDS (mg/L) pose an osmotic pressure of 11 psi or 0.76 bar. To keep a constant TMP across the membrane, a reduction in membrane flux occurs and vice versa. Figure 7 indicates that initially, the membrane flux decreases, however, after a passage of about 120 min the trend transforms nearly smooth at 16.8 LMH. On the other hand, the TMP

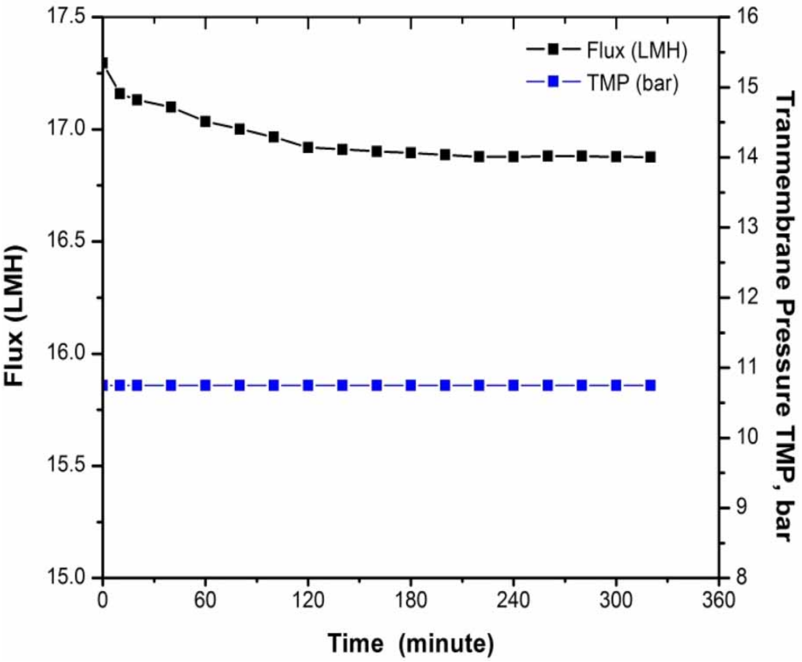

Figure 7 | Membrane flux and TMP at optimized conditions.

across the membrane remains constant due to constant feed pressure. The result findings validate and found according to the studies of Davood Abadi Farahani *et al.* (2016). They utilized three different feed water sources at an optimum pressure of 30 bar for spiral wound RO membrane (model: BW30-365) such as raw untreated feed, coagulation filtration discharge and ultrafiltration discharge. The membrane flux has depicted a sharp drop when untreated feed was utilized which refers to the excessive pore blockage of the membrane due to suspended and colloidal particles. On the other hand, the treated sources such as coagulation filtration discharge and ultrafiltration discharge depicted elevated membrane flux and provided a steady trend.

In the meanwhile, the PR rate of the RO membrane will also decline with the membrane flux. Figure 8 shows the PR rate decline with the passage of time. The PR after some hours become smooth providing a recovery of ~62% with a monthly average of approximately ~61%. Ideally, the RO membranes are designed on the basis of constant flux, so that they may provide a constant product flow. To keep membrane flux constant, TMP increases which adversely affects the membrane performance in terms of reduced permeability leading to membrane fouling. So, the PR declines due to the fouling issues of the membrane. In order to compensate for the variations in the feed water salts concentration and temperature, feed water pressure has been adjusted over time. Khanzada *et al.* (2017) evaluated commercially available Hydranautics RO membrane (model: CPA5-LD-4040) and Filmtec RO membrane (model: LC-LE-4040) with various pretreatment technologies for in-land water treatment. With a specific synthetic feed water TDS concentration (3,500–4,500 mg/L), the Hydranautics membrane resulted in 40% recovery and the Filmtec membrane resulted in 45% recovery. According to the researchers, in the initial 2 h of the operation, the permeability of the Hydranautic membrane decreased by 10 and 13% decrease for the Filmtec membrane which is mainly due to fouling of membrane surface area and concentration polarization. When humic substances and inorganic salt ions (Ca^{2+}) are present in water, a complex gel network can form. The RO membrane is seriously harmed, and the flow is drastically reduced due to the gel network. RO membrane fouling may be managed after electrochemical pretreatment. According to Zhu *et al.* (2021) when the crystal phase of scale shifts from calcite to aragonite, it encourages the development of pliable and flaccid scale layers. The team used an electrochemical approach in softening successfully of the water circulating through the cooling tower.

A complete water analysis of critical parameters of partially treated reject water has been carried out after MMF, ACF and UF treatment. The pH has also been adjusted by dosing sulfuric acid before feeding water to the RO membrane. A higher pH range promotes the precipitation of crucial scale-forming species such as calcium and magnesium and their carbonates and

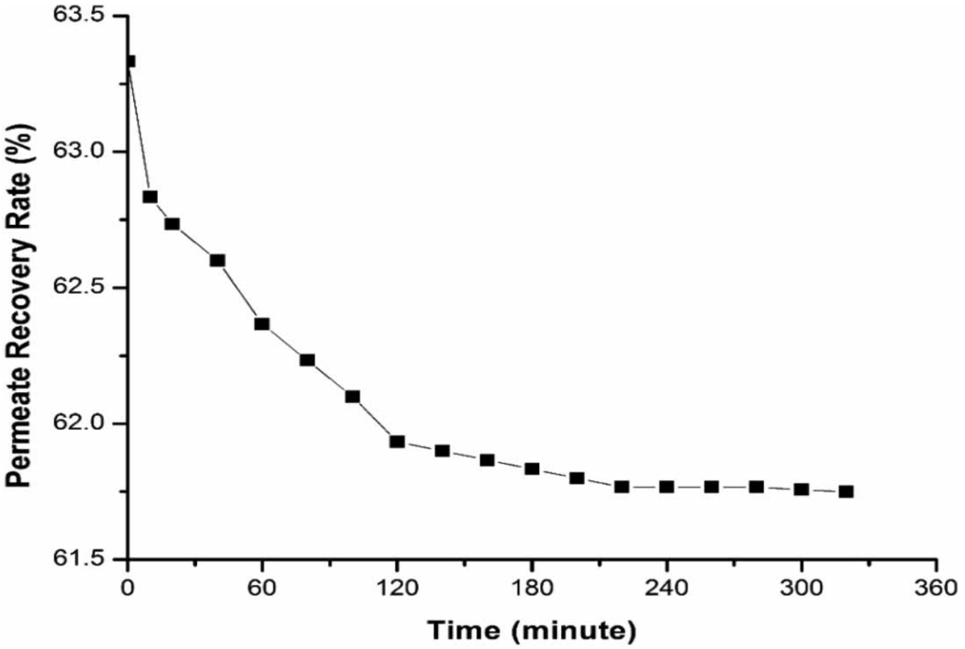

Figure 8 | Change in permeate recovery rate of RO membrane with respect to time.

bicarbonates along with silica. The low pH range keeps the scale-forming agents in soluble form to avoid early RO membrane scaling. After optimizing the governing parameters, the rejected water treatment has been carried out. Table 2 depicts the feed and the permeate water analysis and the rejection rates of critical parameters.

The water auditing has also been carried out taking the rejected streams such as backwash rejects of MMF, ACF and UF. The initial concentrate cleaning water of the RO membrane is also counted. The one-month projected data have been carefully analyzed. The reduction in underground water consumption for the cooling tower has also been calculated. Table 3 presents the water auditing and recovery rates of the concerned water streams.

CTBD and the RO water concentrate water collectively labeled as reject water has been treated by the use of various filters and mainly by RO membrane technology. By considering the reject streams such as backwash water for MMF, ACF, UF and RO membrane concentrate (current system), the overall recovery has been found to be 44.5%. The reject water which is now

Table 2 | RO feed and permeate water analysis and solids rejection rates

		Analysis for RO membrane operation		
Parameter	**Units**	**RO feed water**	**RO permeate (treated water)**	**Rejection (%)**
pH		7.49	7.01	–
Conductivity	μS/cm	2302.2	2015.4	–
TDS	mg/L	1489.9	285.79	80.81
Total alkalinity	mg/L as $CaCO_3$	157.5	20	–
Total hardness	mg/L as $CaCO_3$	1215.41	265.1	78.2
Calcium hardness	mg/L as $CaCO_3$	880.81	240.97	72.64
Magnesium hardness	mg/L as $CaCO_3$	334.60	26.1	92
TSS	mg/L	Nil	Nil	–
Chlorides	mg/L as Cl	89.48	10.11	89
Silica	mg/L as SiO_2	72.7	20.58	71.69
Turbidity	NTU	<0.1	Nil	–

Table 3 | Reject and treated water auditing and recovery rates

Parameter	Flow (m^3/day)	Recovery (%)
Reject water	389.65	
MMF + ACF + UF backwash	38.96	
RO feed	350.69	
RO permeate (and recovery)	216.11	61.6
RO reject	134.58	
Overall wastewater recovery (%)		44.5
Average cooling tower makeup (raw)	45.33	
Average cooling tower makeup (treated)	9	
Total cooling tower makeup	54.34	
Cooling tower raw water makeup reduction		16.56

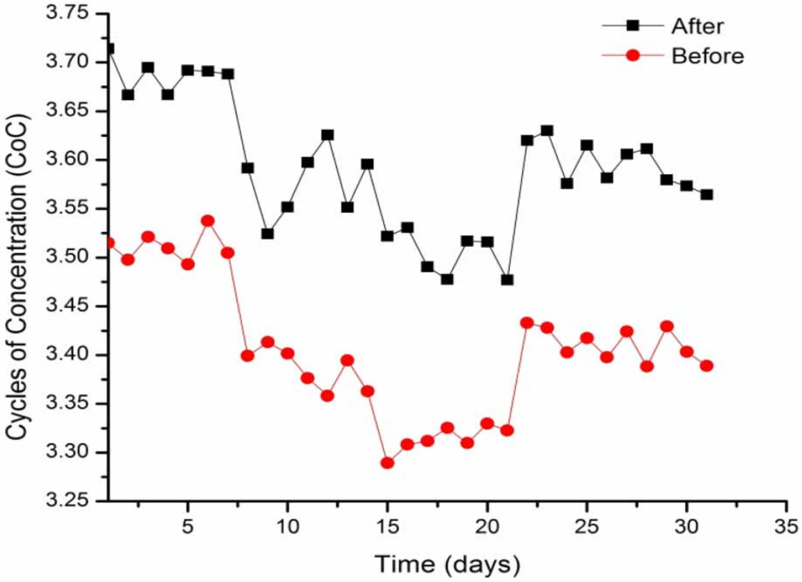

Figure 9 | Cooling tower cycles of concentration before and after treated water utilization.

treated by RO membrane is then continuously reused in the cooling tower process. The treated water reuse has eliminated about 16% of the raw water (fresh) makeup feed of the cooling tower. The trend (labeled as 'before treated water') is depicting the theoretically calculated cycles of concentration (COC) (3.28–3.54) of the cooling tower without the incorporation of the treated water. As the treated water contains less TDS and other critical salts, it increases the COC of the cooling tower from 3.28–3.54 to 3.48–3.7 as depicted in Figure 9. The results are found in appreciable agreement with Altman *et al.* (2012). The results show that the scale-forming ions can precipitate at higher COC. Solubility of the scale-forming species is difficult to sketch due to the incorporation of anti-scalant chemicals. However, at higher concentrations of these scale-forming salts, the anti-scalant chemicals may not be able to prevent scaling. According to Koeman-stein *et al.* (2016), the various scale-forming salts such as Mg^+, Ca^+, HCO_3^-, SO_4^- and Na^+ depict different rates of concentration factors. However, Mg^+, Ca^+, HCO_3^- and SO_4^- showed a less concentration rate as compared to Na^+. Hu *et al.* (2022) characterized various scale-forming constituents in a concentrated alkaline stream of circulating cooling water. According to the researchers, calcium carbonate in the circulating cooling tower was converted to calcium sulfate as the pH dropped from 7.6 to 4.0.

Microbial growth in cooling towers cannot be totally avoided; however, it can be controlled by employing various techniques. The microbial colonies of various bacterial strains can cause biofouling in cooling tower fills which chokes the

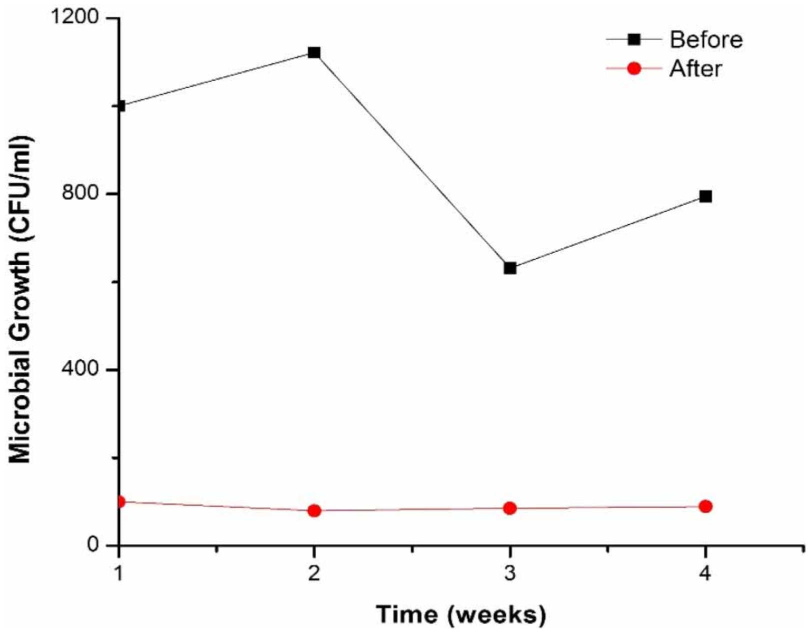

Figure 10 | Microbial growth (total viable/plate count) before and after treated water utilization.

contact between air and water for heat transfer. To evaluate the microbial growth rate in the cooling tower, dip slide tests were performed. Figure 10 depicts tests result before and after incorporating the treated water. Before the incorporation of treated water, the microbial growth rate in the cooling tower has been found up to 10^3 (CFU/mL). After the incorporation of treated water, the microbial growth rate has been found less than 500 (CFU/mL). This is due to the fact that the treated water contains no microbial contamination and is free of any critical nutrient which is essential for anaerobic microbes. Before the treated water reuse in the cooling tower, the residual chlorine was maintained at 0.1 mg/L. After the treated water reuse, the residual chlorine was found to be at 0.2–0.3 mg/L at a constant dose of sodium hypochlorite, which depicts the lower levels of microbial colonies. A visual depiction of the dip slides is elucidated in Figure 11. The agar-based dip slides depict microbial colonies in the form of red spots before and after the reuse of treated water. The dip slide tests after treated makeup water incorporated into the cooling tower show microbial activity of less than 100 CFU/ml, which indicates an optimum biocide dosage. Mohammad (2022) evaluated the efficiency, microbial assessment and system reliability of the reclaimed municipal water for its utilization as an alternative makeup feed water source for cooling tower. According to

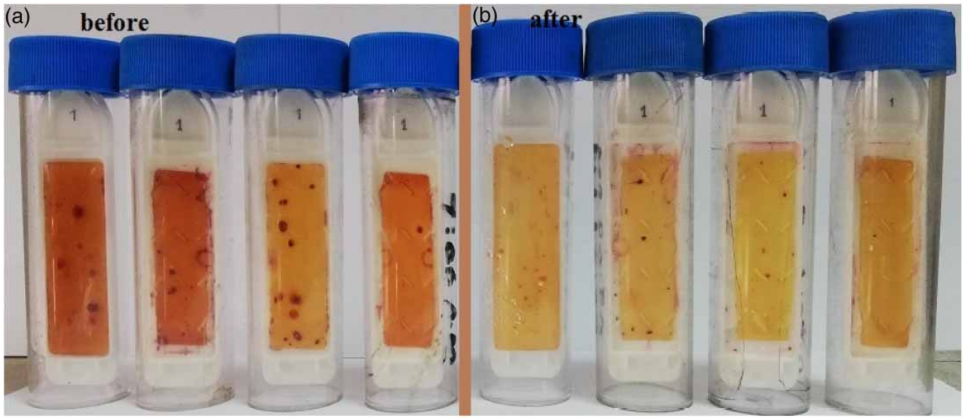

Figure 11 | Visualization of microbial growth (red spots) on dip slides before and after treated water utilization. Please refer to the online version of this paper to see this figure in color: https://dx.doi.org/10.2166/wcc.2023.071.

the authors, biocontamination due to microbial activity is propelled by dust and dirt, nearby field vegetation and other various environmental pollutants. They found out that at optimum biocidal treatment, the microbial activity was hindered which was caused by *Legionella*, total coliform and *Klebsiella*. According to Li *et al.* (2020) macromolecule substances, such as biopolymers, are preferentially adsorbed by the adsorbent in CTBD. Three of the newly found compounds, those with properties like fulvic acid, humic acid and soluble microbial byproducts, showed a clear drop in fluorescence intensity following adsorption. The toxicity study reveals that trichloroisocyanuric acid (TCCA) oxidizing biocides were mostly responsible for the toxicity of CTBD. The toxicity of CTBD was reduced by adsorption, but increased by electrocatalytic oxidation, leading to a subsequent decrease in the toxicity of the desorption eluate. Gene stress analysis suggested that the loss of cellular membrane structure and the disruption of intracellular metabolic balance were caused by wastewater toxicity.

For the corrosion and scaling potential analysis in the cooling tower, coupon tests have been performed before and after the reuse of treated water, as depicted in Figure 12. The first hole-oriented coupon is a mild steel (MS) scale coupon and the other two coupons are corrosion coupons of MS and copper (Cu). A careful analysis of MS and Cu coupon was performed before the reuse of treated water by critically examining of governing factors which cause corrosion. In the present study, corrosion occurs in cooling towers in many forms such as pitting, galvanic, crevice and microbiologically induced corrosion. Pitting is due when the anodic and cathodic sites become stagnant or come at low-velocity situation, also in the presence of a high concentration of chloride ions in a low pH medium. Microbiological corrosion is due to the biofilm formation on the metallic surfaces by microbes. The microbial physical deposition and corrosive metabolic byproducts contribute to the localized intense corrosion. In the present case, the treated water does not contain any suspended particles, debris and microbial species. Due to this, the corrosion rate of MS and Cu coupon was found to be less than the corrosion rate before the reuse of treated water in the cooling tower process. The corrosion rate of MS coupon before and after the reuse of treated water in the cooling tower was found to be 1.54 and 1.43 mpy, respectively. Likewise, the corrosion rate of Cu coupon before and after the reuse of treated water in the cooling tower was found to be 0.669 and 0.524 mpy, respectively. Simultaneously, the scaling in cooling tower occurs due to the accumulation of scale-forming agents such as calcium, magnesium and their carbonates and bicarbonates along with silica and other particulate deposits. According to Mohammad (2022), the localized formation of anodic and cathodic spots leads to the corrosion of steel. The use of corrosion inhibitors is necessary to avoid material loss which may lead to system failure. According to the authors, the rate of corrosion must be less than 5 mpy.

The treated water contains lower levels of scale and fouling-forming species. As depicted in Figure 12, the MS scaling coupon analysis before and after the reuse of treated water in the cooling tower does not depict any significant variation. The slight reduction in the metal surface scaling depicts the lower concentration of scale-forming salts in the cooling tower feed water and the utilization of anti-scalants.

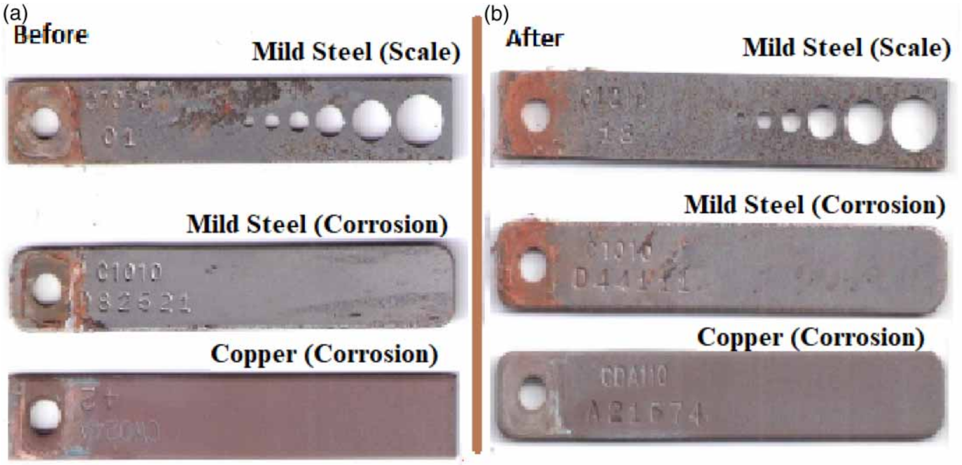

Figure 12 | Visualization of corrosion (C) and scaling (S) coupons for mild steel (MS) and copper (Cu) metallurgy before and after treated water utilization.

4. CONCLUSION

Apart from intensified stress on water resources in various Asian regions, climate change also exacerbates shrinking glaciers, increasing sea level, floods and droughts. Thus, having adequate access to water is crucial to ensure a sustainable future. Reusing water is considered an adaptation strategy since it decreases demands on freshwater resources and boosts water reliability and resilience.

In this work, a combined setup of membranes along with various filters was employed to treat the reject streams of powerplant such as CTBD and RO plant reject water. Various crucial tests and trials were carried out to assess the effectiveness of proposed process and its post-utilization implications. Specifically, we can draw the following conclusions:

1. Ultrafiltration membranes are effective pretreatment technology to pretreat the feed water of the RO membrane. UF membranes ensure feed water $SDI < 3$.
2. Various operating parameters of RO membrane such as feed pressure and temperature have significant effects on the permeate flow and quality such as rejection rates of scale-forming species.
3. The RO membrane had recovered more than 60% of permeate and overall wastewater recovery was found up to 44%. To avoid the scaling of the membrane with the passage of time, advanced anti-scalant chemicals and other pretreatment techniques can be added to completely remove scale-forming salts and this results in increasing the wastewater RO membrane treatment plant productivity.
4. The recycled and reused water incorporation in cooling tower resulted in an effective operation and this ensured the reduction in scaling and corrosion percentage of heat transfer surfaces.
5. The microbial count was significantly reduced in the cooling tower after coupling the recycled water stream. This reduced the utilization of biocides such as sodium hypochlorite and isothiazolinone.
6. To conserve the RO membrane, and concentrate water, zero liquid discharge (ZLD) techniques can be used to increase the overall recovery ratio of reject water.
7. In countries such as Pakistan where water scarcity is intense, the wet-type cooling tower must be replaced by the dry-type cooling towers such as air-cooled condensers to eliminate the use of freshwater resources for environmental sustainability.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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