Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2023.29855

307 (2023) 8–17
September

A pilot study on recycling cooling tower blowdown water through ultrafiltration and reverse osmosis

Jawwad Ahmed[a,*], Amir Younas[b], Yousuf Jamal[c], Muhammad Shujaatullah[a],

[a]*Prime Chemicals Corporation, 223 Anum Blessings, KCHS Blk 7/8, Shahrah-e-Faisal, Karachi, Pakistan, emails: jawwad.ahmed1@gmail.com (J. Ahmed), shujaat@primechemicalscorp.com (M. Shujaatullah)*
[b]*Institute of Environmental Sciences and Engineering, School of Civil and Environmental Engineering, National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan, email: amir.iefr@gmail.com*
[c]*Institute of Chemical Engineering and Technology, University of the Punjab, Lahore, Pakistan, email: yousufjamal.icet@pu.edu.pk*

Received 4 June 2023; Accepted 18 August 2023

ABSTRACT

Recycling of blowdown water from cooling towers through ultrafiltration followed by reverse osmosis has seen progressive development in industrial applications over the years. Whereas published information from pilot studies on the subject has generally indicated favorable results in meeting a water quality acceptable for feed to the reverse osmosis membranes, full-scale applications have met operational challenges, primarily with regard to membrane fouling despite employing elaborate pretreatment schemes as compared to the pilot studies. This work presents the results of a pilot study carried out to recycle cooling tower blowdown water through ultrafiltration followed by reverse osmosis. Contrary to previous studies, it was found that reverse osmosis feed water was not consistently brought within the preferred silt density index value of <3.0 primarily due to the presence of dissolved organics in the water, necessitating more elaborate pretreatment than what is required for conventional groundwater and seawater streams. The present study focused on specific contaminant removal and demonstrated total iron removal of 85.7%, total organic carbon removal of 45.4%, and a total phosphate removal of up to 80.0% through coagulation–ultrafiltration. The study also presents important feedwater characterizations including diurnal cooling tower blowdown temperature profile, particle-size distribution analysis and ultrafiltration membrane flux decay that will help improve system design for recycling cooling tower blowdown water.

Keywords: Cooling tower-blowdown; Phosphate-removal; Ultrafiltration; Reverse osmosis; Pretreatment

1. Introduction

Cooling water for industrial cooling requirements forms the bulk of the overall industrial water use worldwide, with water withdrawals for electric power production alone accounting for half of the global industrial water withdrawals [1]. Water scarcity and the resulting increase in freshwater costs have become drivers for water reclamation and reuse, with attention also on recycling as much water from cooling water systems as possible. The overall water demand for open cooling water systems is made up of water that evaporates in the cooling towers and water that is intentionally wasted as blowdown in order to maintain concentrations of dissolved and suspended impurities in the remaining water within threshold values for corrosion and scale inhibition, along with other losses such as drift and leakages [2]. While effort is also being made to recover the water from evaporating plumes and drift fog

* Corresponding author.

[3,4], recovering water from cooling tower blowdown (CTBD) has also seen focus of attention both in research and in full-scale applications.

Different unit processes have been considered for recycling CTBD water streams. These include nanofiltration [5,6], membrane distillation [7–10], coagulation-settling/filtration [11–13], electrochemical oxidation [14], electrocoagulation [15], vibratory shear enhanced membrane process (VSEP) [16], and ultrafiltration (UF) followed by reverse osmosis (RO) [17–19]. Most reported full-scale applications, however, have used UF followed by RO to recycle the CTBD water. Even so, while pilot studies have generally provided favorable results, literature on full scale applications has shown incidence of operational problems primarily in the form of membrane fouling when treating CTBD water streams [20,21]. Moreover, past studies have tended to ignore the effect of the treatment chemicals used in the cooling water on membrane fouling, leading to consideration of biological treatment processes for the removal of these chemicals [22–24].

Previous work by the authors has identified some of the contaminants of potential concern with regard to treating CTBD water as total organic carbon, phosphate, and iron, beyond some of the parameters which have been considered for removal in previous studies [25]. This work presents the findings of a pilot study carried out to recycle CTBD streams from a fertilizer and power plant complex, with a view to propose an effective treatment scheme for the full-scale recycling facility. The work builds upon previous work on the subject by considering these additional contaminants of concern for removal through a pilot study for recycling a commingled CTBD stream from a fertilizer-power industry in Karachi, Pakistan.

The fertilizer-power plant cooling water mass balance is shown schematically in Fig. 1. Since the purpose of the pilot study was to allow subsequent implementation on full scale, the projected mass balance of the proposed system is shown schematically in Fig. 2, with the recycled water routed back to the fertilizer plant cooling tower as make-up. With the projected improvement in the overall water chemistry of the blended make-up water, additional water savings could be realized by allowing operation at higher cycles of concentration.

2. Materials and methods

2.1. Water quality

The feed water for the present study was taken from two cooling towers. The fertilizer plant cooling tower plant had a maximum allowable chloride concentration in the recirculation water of 250 mg/L, while that of the associated power plant had a maximum allowable chloride concentration of 750 mg/L. The maximum chloride limits were enforced as per the chemical treatment program and the chloride tolerance of the stainless-steel grades used in the cooling water circuit. A portion of the fertilizer plant cooling tower blowdown was already routed to the make-up water of the power plant cooling tower as a water conservation measure. Both cooling towers employed a similar chemical treatment program consisting of ortho-phosphate for primary (anodic) corrosion inhibition, phosphonate for primary calcium carbonate scale inhibition and secondary (cathodic) corrosion inhibition, polymers for calcium phosphate and iron oxide mobilization, and a biocidal program consisting of a combination of bromine and sodium hypochlorite along with a fatty acid amine biodispersant. The cooling water was also dosed with sulfuric acid to maintain the pH at below 8.0.

Physico-chemical parameters of the CTBD streams during initial screening prior to initiation of the pilot study are tabulated in Table 1, along with a range for each parameter from similar past studies for reference. The total iron concentration of the fertilizer and power plant cooling water was 0.37 and 0.78 mg/L, respectively. The blowdown water temperatures were reported to be as high as 43°C.

2.2. Water quality challenges and characterization

The water quality challenges identified for treating the CTBD water streams with RO included the potential for

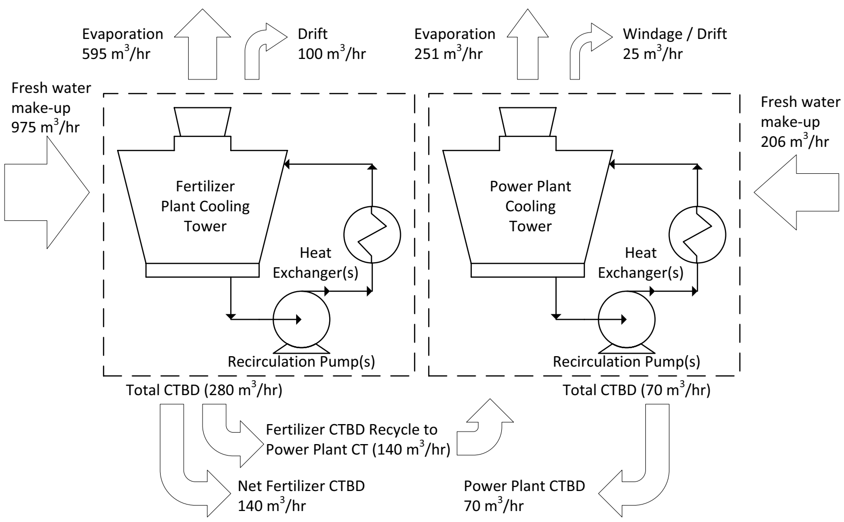

Fig. 1. Current fertilizer plant mass balance and total CTBD generated for both systems.

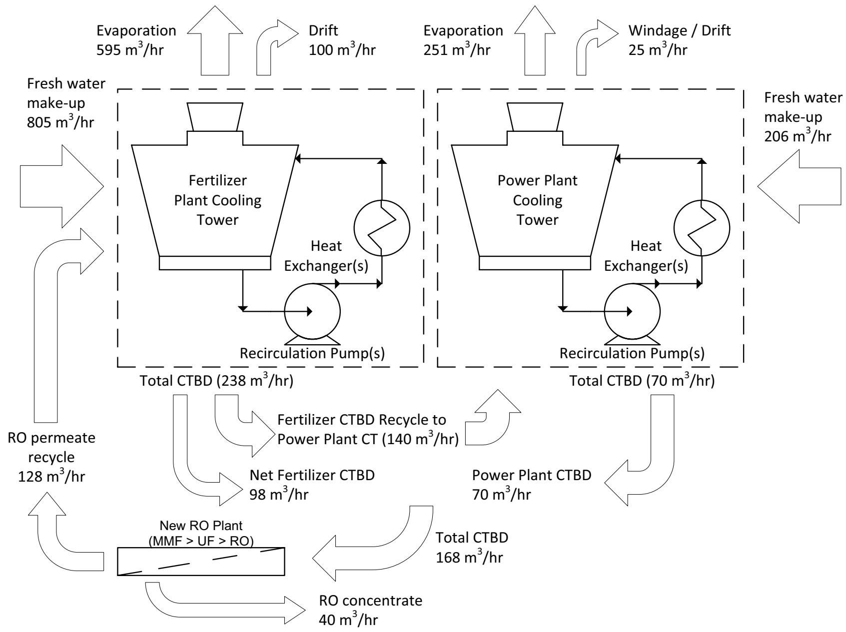

Fig. 2. Projected fertilizer plant mass balance and total CTBD generated for both systems.

Table 1
Physico-chemical parameters of CTBD streams during initial screening

Parameter	Fertilizer plant cooling water	Power plant cooling water	Range from past literature [25]
pH	7.9	7.7	6.7–9.2
Conductivity, μS/cm	1,590	3,305	1,500–7,132
M-Alkalinity, mg/L as $CaCO_3$	140	116	54–356
Sulfate, mg/L	270	808	407–2,341
Chloride, mg/L	236	540	336–766
Phosphate, mg/L	12	20	0.9–8.2
Nitrate, mg/L	14	11	19–88
Silica, mg/L	13.9	28	0.9–140
Calcium, mg/L as $CaCO_3$	178	389	455–1,204
Magnesium, mg/L as $CaCO_3$	151	326	43–470
Sodium, mg/L	144.5	222	332–1,158
Potassium, mg/L	15.8	29.5	52–81
Barium, mg/L	<1	<1	0.145
Strontium, mg/L	1.15	2.41	1.2–1.5
Total suspended solids, mg/L	26	66	10–32
Turbidity, NTU	8.5	22	7–74
Total dissolved solids, mg/L	953	1,983	893–4,749
Total organic carbon, mg/L	6.9	5.8	2–60
Chemical oxygen demand, mg/L	67	124	3.5–181
Biochemical oxygen demand, mg/L	27	41	1.4–8.8

particulate and colloidal fouling, organic and biofouling and scaling. Turbidity was used as a broad parameter to characterize the propensity of particulate and colloidal fouling before and after pretreatment, while TOC (total organic carbon) was used to characterize the same for organic fouling and as a precursor for biofouling. SDI (silt density index) was used to characterize the suitability of the treated water for feed to RO membranes against the preferred value of 3.0 and a maximum acceptable one of 5.0. Based on scale prediction simulations of the feed water, only calcium carbonate and calcium phosphate scaling was expected at the target RO system recovery of 80%. While the solubility of both is pH dependent, phosphate was focused for removal as it has been considered to be a precursor for biofouling by providing nutrients for microorganisms to develop biofilms on RO membranes in previous full-scale applications of CTBD recycling through RO [21].

For this study, UV-Visible Spectrophotometer from the internal laboratory at the fertilizer plant was used for testing for turbidity, phosphate and iron. TOC was tested at an external third-party laboratory through HACH-10129 method (USA). SDI was measured using a potable SDI kit as per the standard test method [26]. A Horiba LA-300 particle size analyzer (Japan) was used to estimate the particle-size distribution of the particles in the water.

2.3. Treatment scheme

CTBD water streams from both cooling towers were mixed in equal proportions and routed to the pilot unit. The pilot unit consisted of a treatment scheme of media filters followed by UF leading up to the RO unit. The media filters were followed by a 100 μ disc filter to prevent carry-over of any loose media onto the UF membrane. Media filters with sand and granular activated carbon were operated at flows corresponding to a filtration velocity of 3.5–5.8 gpm/sq.ft. Bed depths of filter media were kept to 30-inch.

The UF membrane used during the initial phase of the project was a Homespring UF 211 membrane. During the latter phase of the project, the Homespring UF 211 membrane was replaced with a DuPont UF SFD-2660 membrane. Important membrane properties are tabulated in Table 2. Outside-In membranes were specifically chosen in view of the high expected fouling potential of the source water as Outside-In membranes have a lower fouling potential than inside-out [27].

UF membrane was generally operated at conservative flux in the range of 40–60 lmh. Operation of the membrane was done in the following sequence: (i) filtration/service mode: 20 mins, (ii) backwash: 40 s and (iii) forward flush: 20 s.

Table 2
Ultrafiltration membrane properties

	Homespring UF 211	DuPont SFD-2660
Membrane type	Hollow fiber	Hollow fiber
Membrane material	PVDF	PVDF
Nominal pore size	0.02 μ	0.03 μ
Flow direction	Outside-In	Outside-In
Operational mode	Dead-end	Dead-end
Membrane surface area	–	33 m^2

The RO membrane used during the project was a Lanxess Lewabrane B085 HF 4040 spiral wound thin film composite with active polyamide layer and a surface area of 7.9 m^2.

Following parameters were logged on an online data logger: UF feed pressure, UF filtrate pressure, feed water temperature, UF filtrate flow, and feed water conductivity. Additionally, media filter feed and filtrate pressures and operational flows were manually logged on an hourly basis.

The commingled feed water stream before the media filters was dosed with polyaluminum chloride (PACl) as coagulant followed by in-line mixing in a pipe-type flocculator. Coagulant choice was based on the findings of previous studies treating CTBD streams [11,13], and a coagulant dose of 28 mg/L was found to be suitable for formation of visible filterable flocs based on *in-situ* jar testing.

The final treatment scheme consisted of coagulant dosing followed by a two-stage media filter, 100 μ disk filter, and UF leading up to the RO. Intermediate tanks were used to allow balancing of flows. Final pretreated water for RO feed was routed through a 1 μ cartridge filter. The scheme is shown in Fig. 3. Fig. 4 shows snapshots of the media filters and UF membrane set-up.

3. Results and discussion

3.1. Water quality

3.1.1. Feed water temperature

Fig. 5 shows the average monthly diurnal temperature of the commingled CTBD water streams for the two hottest months (April 2019 and October 2019) in which the pilot study was carried out. While the mean water temperatures were generally well below 40°C (mean of 31.5°C for both months), the instantaneous maximum and upper quartile water temperatures can be seen to be touching the 40°C mark, which is considered to be the upper threshold for the commonly used polyvinylidene difluoride (PVDF) membranes [28].

3.1.2. Media prefilters performance

During the initial pilot run with media filters alone, no reduction in total phosphate was observed. The media filters were able to reduce total iron from 0.48 to 0.25 mg/L, and turbidity from 18.8 to 11.2 NTU. Water samples were subjected to analysis of particle size to ascertain

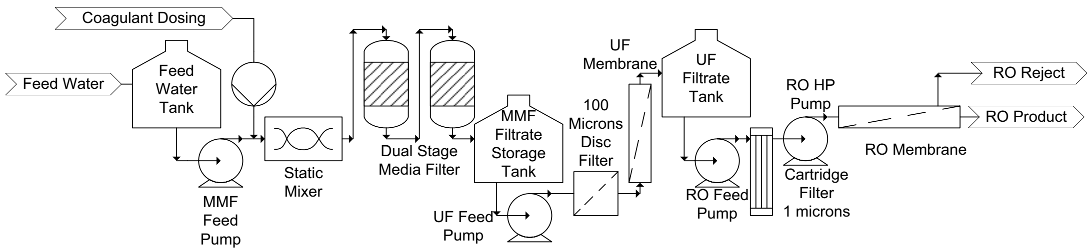

Fig. 3. Final treatment scheme for treating CTBD water.

Fig. 4. Media filter (left) and ultrafiltration membrane (right).

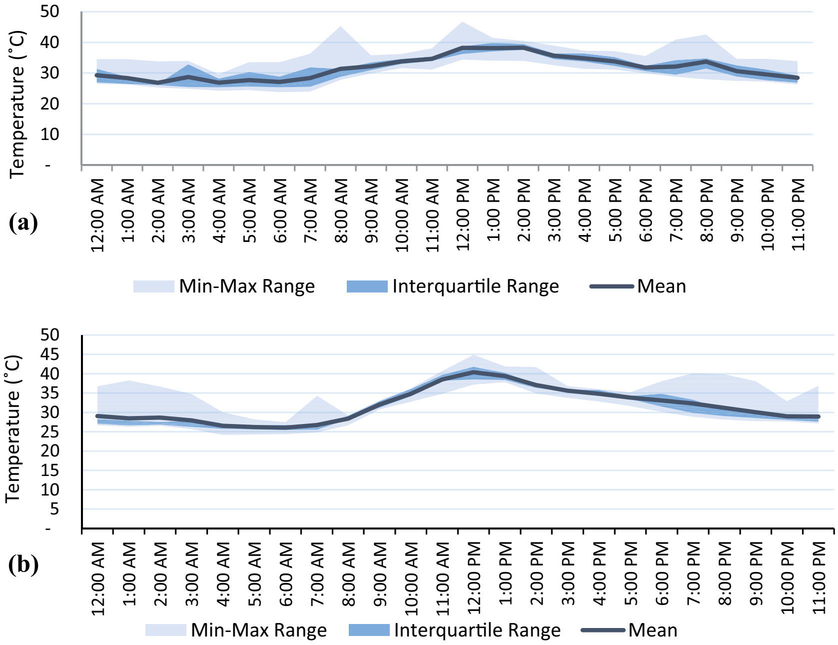

Fig. 5. Average monthly diurnal feed water temperature (a) Apr-2019 and (b) Oct-2019.

the effective nominal filtration rating of the media filter. Fig. 6 shows the particle-size distribution of (a) the feed water, and (b) filtrate from the media filtration. A statistical summary is presented in Table 3, showing an effective nominal porosity of 39 μm for the media filter, which explains the poor reduction of turbidity as the feed water particle size is of the same order of magnitude as the media filters' effective porosity.

The feed water particle size and performance of the media filters in not being able to consistently reduce turbidity to <10 NTU or reduce the phosphate at all necessitated the use of membrane filtration as the primary pretreatment technology. Furthermore, membrane filtration porosity selection guideline of using a porosity of one-tenth the particle size also suggests why, despite limited studies, microfiltration has been demonstrated to have similar performance as ultrafiltration for this application [29–32].

3.1.3. Treatment scheme filtration performance

Ultrafiltration membrane was added downstream of the media filters in the second stage. Fig. 7a shows the performance of the overall treatment scheme in reducing turbidity. A median feed water turbidity of 33 NTU was consistently reduced to <1 NTU throughout. As shown in Fig. 7b, the filtrate SDI was brought to <5.0, although a few datasets between 5.0 and 6.0 were also recorded. Even so, the filtrate SDI was not consistently recorded in the desirable range for RO feed waters of <3.0.

Iron is another recognized foulant for RO membrane. Fig. 8 shows a reduction in total iron across the filtration scheme, which was reduced from a median value of over 0.7 mg/L to around 0.1 mg/L. The results in the preceding discussion and Figs. 7 and 8 show an otherwise satisfactory rejection of particulates and colloids in the form of

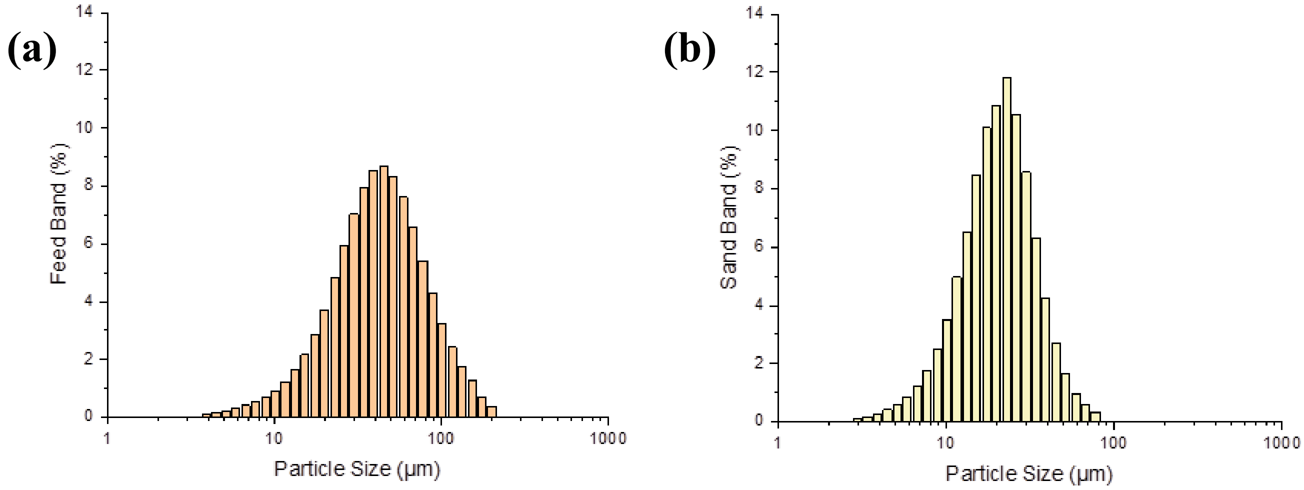

Fig. 6. Feed and media filter filtrate stream particle-size distribution.

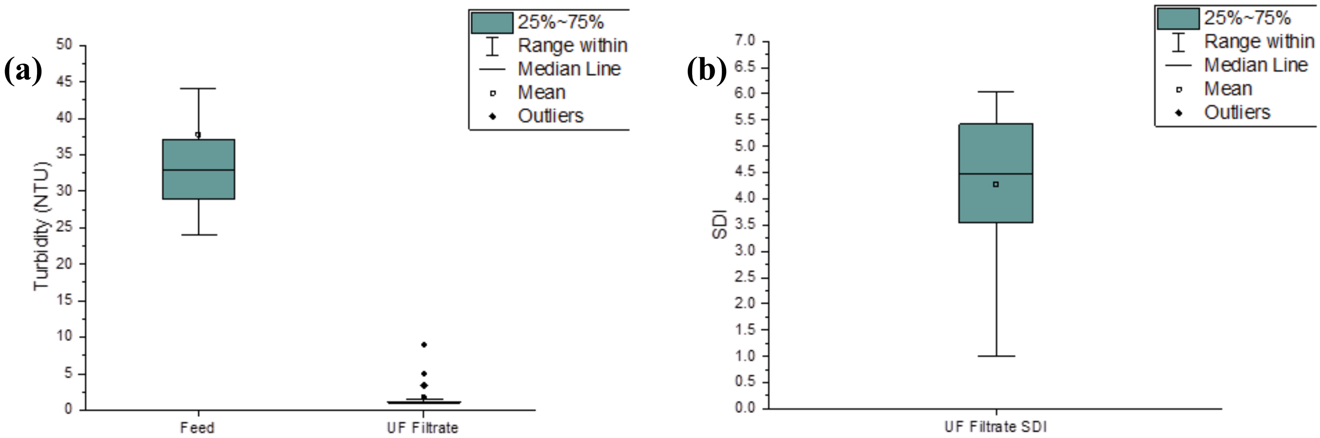

Fig. 7. (a) Feed and UF filtrate turbidity and (b) UF filtrate SDI.

Table 3
Feed and media filtrate particle size statistical summary

	Feed water	Media filter
Mean particle size (µm)	47.22	21.99
Standard deviation	30.98	14.12
Equivalent nominal micron rating (µm)	88.58	39.23

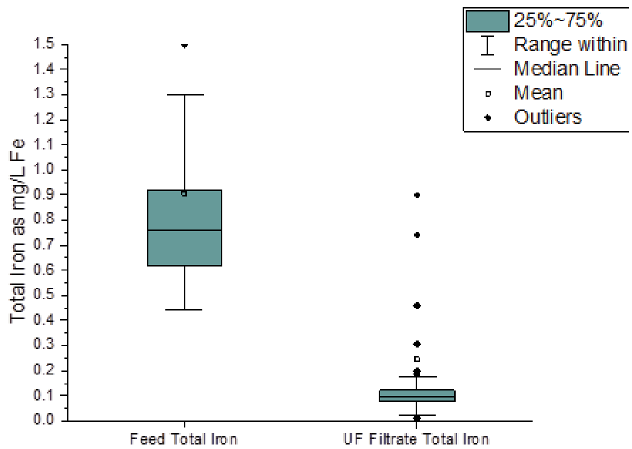

Fig. 8. Feed and UF filtrate total iron.

turbidity and iron, but the SDI values were still noted to be beyond the preferable range of 3.0.

Fig. 9 shows the reduction in total organic carbon (TOC) across the filtration scheme, which was reduced from a median value of over 10.0 mg/L to around 6.0 mg/L, which is still well above the recommended value of <2.0 mg/L for feed water for RO [33]. These results suggest that TOC may be the cause of high SDI values downstream of the UF membrane. While the SDI filter porosity of 0.45 µ is an order of magnitude larger than that of the UF membranes' porosities of 0.02–0.03 µ, clogging of the SDI filter is still possible through adsorption of the organics on the mixed cellulose ester cross-section of the SDI filters due to the hydrophobic nature of the filter material [34]. Fig. 10 shows scanning

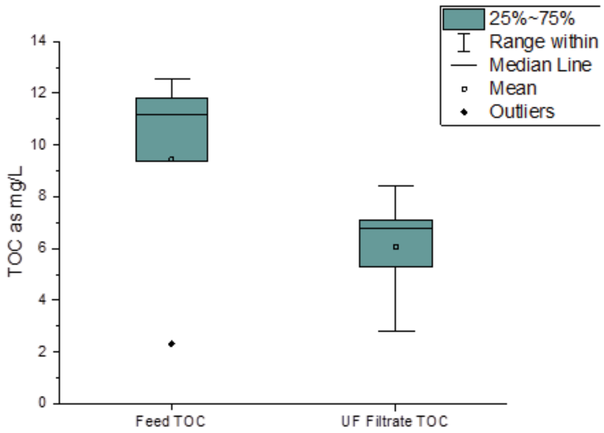

Fig. 9. Feed and UF filtrate total organic carbon.

electron microscope images of (a) virgin SDI filter and (b–c) used SDI filters with SDI values of >5.0 at a magnification of 500–1,000x, which suggests a build-up of an amorphous cake layer on the filter, and formation of what appear to be distinct microbial colonies on the filter surface indicating the advent of biofouling in addition to organic fouling. These results are in agreement with what has been reported for full-scale applications of CTBD recycling, using media filtration followed by UF and RO, in that organic and biofouling have been noted as definite concerns [20]. Furthermore, the CTBD water streams also contained phosphorous in the form of ortho-phosphate and phosphonate as noted in the previous section. Full-scale study on CTBD recycling by Qi et al. [21] notes the role of phosphorus as a nutrient available for uptake by microorganisms in contributing towards biofouling.

Results for phosphate removal are plotted in Fig. 11. Fig. 11a shows a reduction of 15% for 0.02 μ UF membrane

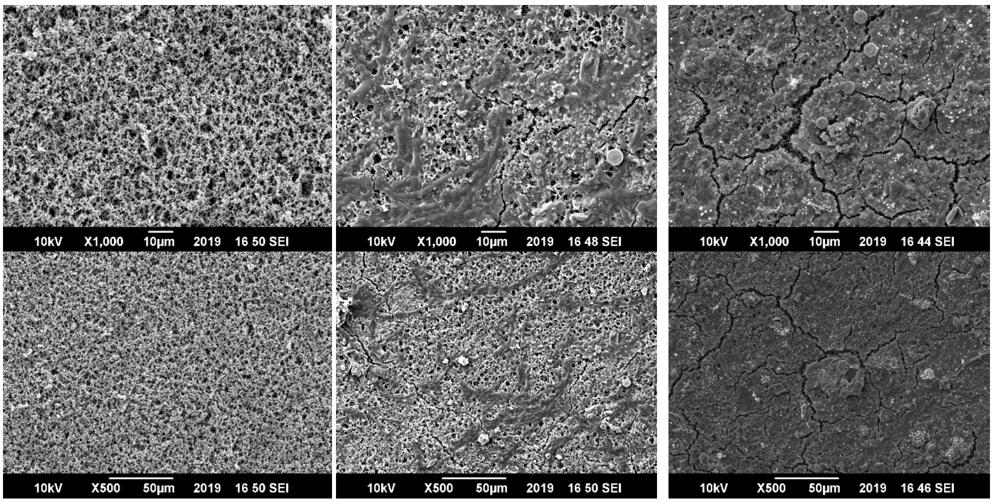

Fig. 10. (a) Virgin SDI filter, (b–c) used SDI filter (SDI > 5.0) at 500–1,000 magnification.

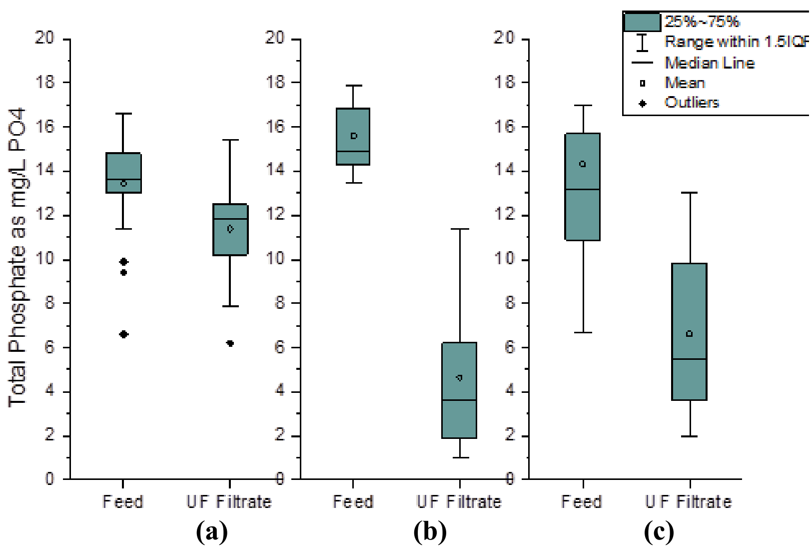

Fig. 11. Feed and UF filtrate total phosphate for (a) 0.02 μ UF, (b) 0.02 μ UF preceded by inline coagulation, and (c) 0.03 μ UF preceded by inline coagulation.

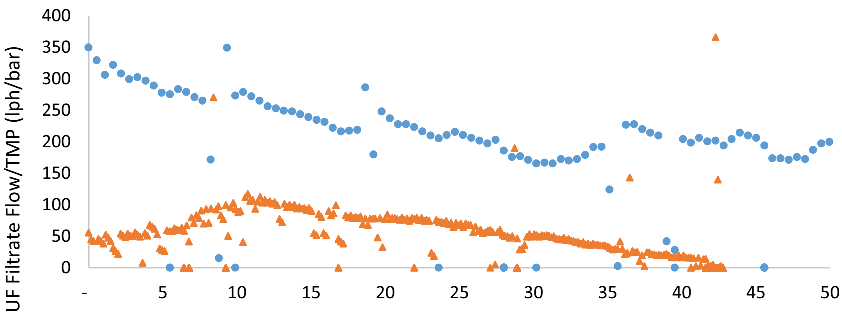

Fig. 12. Ultrafiltration filtrate flux (L/h·bar) decline with and without upstream media filter.

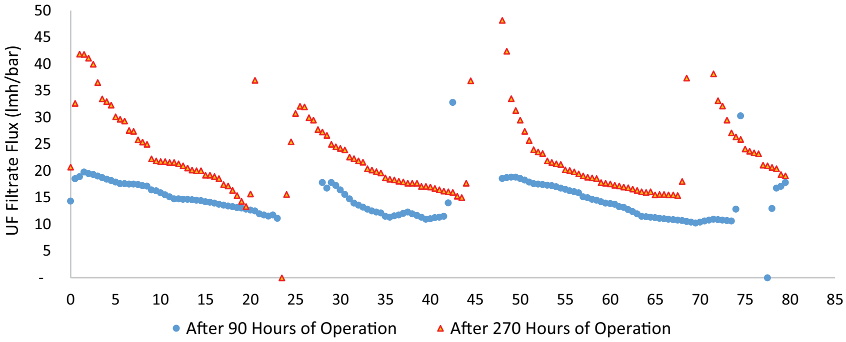

Fig. 13. Ultrafiltration filtrate flux (lmh·bar) profiles up to 270 h of operation.

without upstream in-line coagulation. Fig. 11b shows a reduction of as much as 80% reduction for the 0.02 μ UF membrane preceded by in-line coagulation. Fig. 11c shows around 50% reduction in the total phosphate level for the 0.03 μ UF membrane preceded by in-line coagulation. While these removal rates would be enough to mitigate the potential of calcium phosphate scaling, even the higher removal rates would still entail enough residual phosphorus in the UF permeate to be a cause of concern as a precursor to biofouling.

3.1.4. Ultrafiltration membrane fouling and flux decline

In addition to the efficacy of the treatment scheme in removing the contaminants of potential concern, the present work also studied the UF membrane filtrate flux as a means of judging the extent of the fouling and sustainability of the UF membrane and upstream unit processes in meeting the feed water requirement for the downstream RO membrane. Fig. 12 shows the flux decline for the operation of the Homespring UF 211 UF model with and without an upstream media filter. Without an upstream media filter, the UF filtrate flux decayed terminally with normal backwash cycles even when operated at lower flux rates than when operated with an upstream media filter.

Fig. 13 plots the flux decay profile of the UF membrane in the last phase of operation. Two profiles are shown, one each of three operational cycles of up to 80 min of operation after 90 and 270 h of operation. The terminal flux for both profiles appears uniform suggesting that fouling in the membranes was almost totally reversible till 270 h of operation.

4. Conclusion

Recycling CTBD streams through UF-RO has previously been demonstrated to be a technically feasible proposition through various demonstrations on pilot and full scale. This study provides additional insights that will be of benefit in coming up with an integrated design guideline similar to those for conventional brackish and seawater sources.

The current work adds to the existing published information on the subject by utilizing additional characterization measures including the particle-size distribution of the feed water to argue that although UF membranes have been a popular choice for pretreatment of the CTBD water streams, microfiltration may well yield equivalent results. Additionally, by presenting the diurnal CTBD water temperature profile, we argue that recycling CTBD stream in warmer climates through directly coupled UF-RO systems may potentially entail feedwater temperatures to exceed thermal limits of conventional PVDF UF membrane material, and care must be exercised for system design and material selection. We also emphasize on the need for having a robust pretreatment system wherein fouling in UF membranes may be mitigated through the use of upstream media filters, something which has not been covered in past pilot studies on the subject.

We also note the limitation of the UF system in removing dissolved organic carbon from the water. The organic content, in addition to the phosphate in the CTBD water streams, presents a residual risk of organic and biofouling on downstream RO membranes, necessitating the use of biocides and additional unit processes in full-scale applications.

Despite these challenges, recycling CTBD stream presents an opportunity of reducing the water footprint of open recirculating cooling water systems. The direct and indirect water savings can be around 15% of the total water consumption of such systems, which is in line with estimates published in previous studies [35–37]. As shown in Fig. 2, with an overall recycling system target recovery of 76%, the proposed project on full scale promises a projected reduction of 14.4% in the total freshwater withdrawal and up to 80% in the total wastewater generated from the cooling towers. The recycled water cost was worked out using the projected operational costs and amortized capital costs to be USD 0.75/m^3. This was around 20% lower than the purchase price of freshwater from the municipality after accounting for inflationary impacts over the project life-cycle. This shows that recycling cooling tower blowdown water not only has the potential of reducing the water footprint and wastewater volumes generated, but can also be an economically sustainable endeavor.

References

[1] E.G. Davies, P. Kyle, J.A. Edmonds, An integrated assessment of global and regional water demands for electricity generation to 2095, Adv. Water Resour., 52 (2013) 296–313.

[2] D.J. Flynn, The Nalco Water Handbook, McGraw-Hill, New York, 2009.

[3] M. Damak, K.K. Varanasi, Electrostatically driven fog collection using space charge injection, Sci. Adv., 4 (2018), doi: 10.1126/sciadv.aao5323.

[4] R. Ghosh, R. Ganguly, Fog harvesting from cooling towers using metal mesh: effects of aerodynamic, deposition, and drainage efficiencies, J. Power Energy, 234 (2020) 994–1014.

[5] C. Dhokai, R.R. Palkar, V. Jain, Water saving in thermal power plant by use of membrane filter in cooling tower treatment, AIMS Environ. Sci., 9 (2022) 298–308.

[6] X.-Q. Zhang, X. Han, X. Zhang, S.-Q. Yang, M.-X. Du, A partial feed nanofiltration system with stabilizing water quality for treating the sewage discharged from open recirculating cooling water systems, Sep. Purif. Technol., 234 (2020) 116045, doi: 10.1016/j.seppur.2019.116045.

[7] X. Yu, H. Yang, H. Lei, A. Shapiro, Experimental evaluation on concentrating cooling tower blowdown water by direct contact membrane distillation, Desalination, 323 (2013) 134–141.

[8] N.E. Koeman-Stein, R.J. Creusen, M. Zijlstra, C.K. Groot, W.B. van den Broek, Membrane distillation of industrial cooling tower blowdown water, Water Resour. Ind., 14 (2016) 11–17.

[9] J. Ma, H.M. Irfan, Y. Wang, X. Feng, D. Xu, Recovering wastewater in a cooling water system with thermal membrane distillation, J. Ind. Eng. Chem., 57 (2018) 10491–10499.

[10] M. Ince, Y.A. Uslu, E. Ince, H. Yasar, The effects of pretreatment on membrane distillation of cooling tower blowdown water, Membr. Water Treat., 12 (2021) 285–292.

[11] M.H.D.A. Farahani, S.M. Borghei, V. Vatanpour, Recovery of cooling tower blowdown water for reuse: the investigation of different types of pretreatment prior nanofiltration and reverse osmosis, J. Water Process Eng., 10 (2016) 188–199.

[12] J. Löwenberg, J.A. Baum, Y.-S. Zimmermann, C. Groot, W. van den Broek, T. Wintgens, Comparison of pre-treatment technologies towards improving reverse osmosis desalination of cooling tower blow down, Desalination, 357 (2015) 140–149.

[13] J.M. Frick, L.A. Féris, I.C. Tessaro, Evaluation of pretreatments for a blowdown stream to feed a filtration system with discarded reverse osmosis membranes, Desalination, 341 (2014) 126–134.

[14] P. Saha, H. Bruning, T.V. Wagner, H.H.M. Rijnaarts, Removal of organic compounds from cooling tower blowdown by electrochemical oxidation: role of electrodes and operational parameters, Chemosphere, 259 (2020) 127491, doi: 10.1016/j.chemosphere.2020.127491.

[15] E.A. Anwer, B.A. Abdulmajeed, Electrocoagulation for treatment of simulated blowdown water of cooling tower, J. Eng., 26 (2020) 1–14.

[16] M. Soliman, F. Eljack, M.-K. Kazi, F. Almomani, E. Ahmed, Z. El Jack, Treatment technologies for cooling water blowdown: a critical review, Sustainability, 14 (2022) 376, doi: 10.3390/su14010376.

[17] B.C. Boda, V. Pawde, G.S. Rawat, Cooling Tower Blowdown Water Treatment by UF/RO Membranes on Cement Plant in the UAE, The International Desalination Association World Congress on Desalination and Water Reuse, International Desalination Association, San Diego, CA, 2015.

[18] C. Groot, W. Van Den Broek, J. Loewenberg, N. Koeman-Stein, M. Heidekamp, W. De Schepper, Mild desalination of various raw water streams, Water Sci. Technol., 72 (2015) 371–376.

[19] X.L. Santos NOd, V.R. Oliveira, G.T. Ribeiro, L. Yokoyama, Pretreatment of Blowdown Cooling Tower Water for Reuse, The International Desalination Association World Congress, International Desalination Association, São Paulo, Brazil, 2017.

[20] L. Wanbing, The application of UF and RO in the treatment of the circulating cooling tower blowdown water, Guangdong Chem. Ind., 14 (2014) 163–164.

[21] J. Qi, L. Ruirui, L. Fangyu, S. Yan, Optimization of membrane method used for circulating water system in thermal power plant, Ind. Saf. Environ. Prot., 40 (2014) 93–95.

[22] T.V. Wagner, J.R. Parsons, H.H.M. Rijnaarts, P. de Voogt, A.A.M. Langenhoff, A review on the removal of conditioning chemicals from cooling tower water in constructed wetlands, Crit. Rev. Env. Sci. Technol., 48 (2018) 1094–1125.

[23] T.V. Wagner, J.R. Parsons, H.H.M. Rijnaarts, P. de Voogt, A.A.M. Langenhoff, Benzotriazole removal mechanisms in pilot-scale constructed wetlands treating cooling tower water, J. Hazard. Mater., 384 (2020) 121314, doi: 10.1016/j.jhazmat.2019.121314.

[24] T. Wagner, P. Saha, H. Bruning, H. Rijnaarts, Lowering the freshwater footprint of cooling towers: a treatment-train for the reuse of discharged water consisting of constructed wetlands, nanofiltration, electrochemical oxidation and reverse osmosis, J. Cleaner Prod., 364 (2022) 132667, doi: 10.1016/j.jclepro.2022.132667.

[25] J. Ahmed, Y. Jamal, M. Shujaatullah, Recovery of cooling tower blowdown water through reverse osmosis (RO): review of water parameters affecting membrane fouling and pretreatment schemes, Desal. Water Treat., 189 (2020) 9–17.

[26] A. D4189-07, Standard Test Method for Silt Density Index (SDI) of Water, ASTM International West Conshohocken, PA, 2007.

[27] R. Kaya, A. Yuksekdag, S. Korkut, T. Turken, M.E. Pasaoglu, M.E. Ersahin, H. Ozgun, I. Koyuncu, Impact of membrane configuration on the performance and cost of a pilot-scale UF process treating surface water, Sep. Purif. Technol., 304 (2023) 122414, doi: 10.1016/j.seppur.2022.122414.

[28] X. Shi, G. Tal, N.P. Hankins, V. Gitis, Fouling and cleaning of ultrafiltration membranes: a review, J. Water Process Eng., 1 (2014) 121–138.

[29] M. Cheryan, Ultrafiltration and Microfiltration Handbook, CRC Press, Boca Raton, Florida, 1998.

[30] L.-q. Yin, X.-y. Guan, Application of continuous microfiltration tubular membrane in power plant recycle cooling water treatment, J. Filter Separator, 3 (2005) 33–35.

[31] Z. Wang, Z. Fan, L. Xie, S. Wang, Study of integrated membrane systems for the treatment of wastewater from cooling towers, Desalination, 191 (2006) 117–124.

[32] J. Zhang, L. Chen, H. Zeng, X. Yan, X. Song, H. Yang, C. Ye, Pilot testing of Outside-In MF and UF modules used for cooling tower blowdown pretreatment of power plants, Desalination, 214 (2007) 287–298.

[33] N. Voutchkov, Desalination Engineering: Planning and Design, McGraw Hill Professional, Maidenhead, England, 2012.

[34] H. Iwahori, S. Ishihara, M. Ando, N. Tada, Peculiar or Unexpected Behavior of Silt Density Index of Pretreated

Seawater for RO Desalination, The Proceedings of the IDA World Congress at Bahamas, 2003.
[35] S.J. Altman, R.P. Jensen, M.A. Cappelle, A.L. Sanchez, R.L. Everett, H.L. Anderson Jr., L.K. McGrath, Membrane treatment of side-stream cooling tower water for reduction of water usage, Desalination, 285 (2012) 177–183.
[36] R. Jain, H. Nigam, M. Mathur, A. Malik, U.K. Arora, Towards green thermal power plants with blowdown water reuse and simultaneous biogenic nanostructures recovery from waste, Resour. Conserv. Recycl., 168 (2021) 105283, doi: 10.1016/j.resconrec.2020.105283.
[37] S.L. Plata, C.L. Devenport, A. Miara, K.A. Sitterley, A. Evans, M. Talmadge, K.M. Van Allsburg, P. Kurup, J. Cox, S. Kerber, A. Howell, R. Breckenridge, C. Manygoats, J.R. Stokes-Draut, J. Macknick, A.E. Childress, Zero liquid discharge and water reuse in recirculating cooling towers at power facilities: review and case study analysis, ACS Sustainable Chem. Eng., 2 (2022) 508–525.