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Adaptability of membrane filtration systems under different treatment options for textile wastewater management in an industrial cluster

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ABSTRACT

Textile manufacturing requires extensive quantity of raw materials such as dyes, salts and water in the process with resultant discharge of these in the wastewaters generated. Indiscriminate disposal of textile effluents in a town located in South of India has severely damaged the ground and surface waters in the area. Current emphasis on protecting the water bodies in the town through tough regulatory compliances following zero discharge has laid the industries as well as regulatory agencies in dilemma. This has resulted in implementation of various treatment options to meet the regulatory norms and water recovery. Recent developments in membrane and advanced oxidation techniques have resulted in having alternatives for the treatment of textile effluent in the cluster. The paper addresses to the case study undertaken in the textile cluster to study operational textile effluent treatment plants employing a combination of unit operations and processes (UO&P) technologies to comply with zero effluent liquid discharge norms. The paper discusses various costs involved in different UO&P options of different technologies are presented here to highlight a sustainable wastewater management with resource recovery.

Keywords: Textile effluents; Water recovery; Advanced oxidation; Membrane filtration; Cost analysis

1. Introduction

Textile sector in India is a major source of employment and foreign exchange earner. It is also the second largest textile manufacturer in the world after China [1]. It is expected to touch 115 billion US dollars by the year 2012 and contributes to about 4% of gross domestic product [2,3]. Indiscriminate disposal of textile effluents has damaged the surface and ground waters in and around various industrial clusters in the country and making them unfit by addition of colours, shifting of pH, increase in salt concentration and organic load etc., [4]. One such major textile center in Southern India has developed rapidly in the last few decades. Since then the development has polluted the surface and ground water to such an extent that irrigation in the district has been affected grossly [5,6]. Apart from this, the quantity of freshwater available to the industry has been reducing drastically over the years from competing users' viz., domestic, agriculture and other industry [7].

The UN General Assembly has declared the decade 2005–2015 as the ''International Decade for Action: Water For Life'', bringing the challenges of protecting

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drinking water reserves, dealing responsibly with water resources, effective distribution and sustainable water management through recycling, firmly into the spotlight [8]. This declaration is binding on all the world governments and leads to a firm decision on protecting the water bodies globally through affirmative actions. The main challenge for the textile industry in the country today was to bring modifications in production process and end of pipe treatment. Eco-friendliness of the industry can be brought by use of safer dyes and chemicals and recovering resources from the wastes [9]. Recycling/reuse of renovated water have become a necessity in the town and considered the most practical solution.

The emphasis on protecting water bodies through compliance with the zero discharge in the country has seriously upset the textile wastewater management. This task has resulted in arriving at various technological options to recover water from the textile industry economically [10]. The major problems attributed to the zero discharge schemes are addition of multiple processes and operations for removal of various pollutants in the effluent to meet recyclable water quality [11]. Recent developments in membrane filtrations systems and advanced oxidation technologies have resulted in having treatment alternatives to the conventional textile wastewater treatment [12–15]. Various technologies have been transferred from laboratory to full scale levels without considering the cost economics of the treatment scheme [5,16,17]. Normally technologies are accepted under rigorous field testing with great deal of field assessment; however, under regulatory pressure quick decision-making enforces implementation without considering the cost economy of the treatment technology.

The study was undertaken for the textile cluster to assess the operational textile effluent treatment plants (ETPs) employing a combination of UO&P to achieve zero liquid effluent discharge and comply with regulatory norms. The salient features of the studies include performance assessment and evaluation of different treatment combinations in the pretreatment and advanced treatment modules of textile wastewater management in the cluster. The costs incurred towards capital investment and operational costs are presented to provide an idea on the costs of zero effluent liquid discharge in textile waster management. Other highlights of the study are resource recovery such as salt and water from the effluents generated from the individual units. A perfect treatment scheme is the intersection of interests of the stakeholders (industry, regulatory agency, public and wastewater managers) concerned and would result in sustainable development of the industry.

2. Materials and methodology

2.1. Case study of the area and the wastewater management

The town under study has around 730 textile units manufacturing T-shirts, undergarments, and casual wears for export market and consumption within the country. The textile units have been directed to achieve zero liquid effluent discharge to protect the already polluted surface and ground water bodies in and around the city. The industrial units have invested in a combination of conventional and advanced treatment unit operations and processes to meet the objectives. Various UO&P's have been adopted for textile effluent management in the town and is presented in Table 1 along with the inland surface water discharge standards of the area. All the textile dyeing units present in the town follow one of the combinations presented in this manuscript to manage effluent individually or through a Common Effluent Treatment Plant (CETP) facility. The CETPs also follow similar schemes, except that the scale of treatment is slightly larger. Textile wastewater management in the cluster follows a conventional treatment at primary and secondary stages comprising chemical precipitation followed by biological treatment. The pretreatment module consists of conventional and advanced oxidation effluent treatment process and the recovery module consist of various stages of membrane filtration systems which include micron, ultrafiltration, nanofiltration and reverse osmosis membranes. The rejects from these are either sent to solar evaporation pans for drying or to multiple effects evaporator for salt recovery.

2.2. Wastewater management in the textile cluster

The wastewater management in the textile cluster generally follows the treatment combinations indicated in Table 2. Generally two streams (dye bath and wash water) contribute to the effluents from the textile units. They are treated separately or as combined effluent owing to reasons such as space constraints for collection of dye bath and wash water streams separately. In the conventional pre-treatment chemical precipitation through lime and ferrous sulphate\ferric chloride is used for stage 1 of effluent pre-treatment. However, some of the units have gone for electroprecipitation and advanced oxidation process such as ozonation and electrochemical oxidation. All the treatment is briefly explained in Table 2. Stage 2 consists of aerobic biological treatment for reduction of soluble organic matter. Extended aeration mode of activated sludge process is operated to provide ample time for the biodegradation. In the third stage, the effluent is treated through dual media filtration and activated carbon adsorption

Table 1
Generalized effluent treatment processes of targeted pollutants in the textile cluster

Unit treatment process	Agent	Pollutant	IS Standards for discharge into surface water bodies	
Neutralization	Sodium hydroxide	pH reduction as most of the effluents in the cluster are alkaline in nature	pH	5.5 to 9.0
Chemical precipitation	Lime, ferrous sulphate, Polyelectrolyte	Colour, turbidity, suspended solids	-	-
Ozonation	Ozone	Colour, organic matter		
Anaerobic degradation	Biodegradation Through anaerobic bacteria	Colour, organic matter	BOD COD,mg.l^{-1}	30 250
Activated sludge process	Biodegradation Through aerobic bacteria	Organic matter		
Effluent polishing	Sand filtration, activated carbon adsorption	Colloidal and suspended	SS, mg.l^{-1}	100
Membrane filtration	MF, UF, NF, RO	Inorganic/ dissolved salts/ heavy metals	TDS, mg.l^{-1} Cl, mg.l^{-1}	2100 1000

Abbreviation
BOD – Biochemical Oxygen Demand
COD – Chemical Oxygen Demand
SS – Suspended Solids
TDS – Total Dissolved Solids
Cl – Chlorides

or may be treated again through chemical precipitation. Few of the textile units treat effluent upto stage 4.

In the recovery module treatment, the pretreated effluent is treated through multistage membrane systems. In the first stage of recovery module, the combined effluents are treated through brackish water reverse osmosis membrane whose rejects are further treated through sea water reverse osmosis membrane in further stages. The operating pressure range and overall recovery from the membrane stage are presented in Table 3. If dye bath is separated then nanofiltration membranes recover the brine (sodium salt solution) and are reused in the process. The rejects (divalent salt solution) are sent to solar evaporation pans or multiple effects evaporator for drying. About 90% of the units employed spiral wound polyamide membranes for water and salt recovery.

2.3. Selection of textile units having different wastewater management

The textile units have employed various treatment options to comply with zero liquid discharge (ZLD) norms. The best operating effluent treatment units were selected for ZLD and were categorized into different treatment combinations (C1, C2, ..., C8) and assessed for their treatment performance and associated costs of the combination. The treatment options implemented in the town are presented in Table 2. Hence the study is limited to individual units with different treatment options for wastewater management. Eight treatment options have been employed in the textile cluster. The treatment combinations have been represented as C1, C2 and so on in all the tables.

The pretreatment schemes have been designed to run throughout the day under maximum load. However, during the assessment period all the textile units were operating below the design hydraulic flows. Feed to membrane indicates adjustment of feed effluent quality to membrane by pH adjustment, solids removal through micron/cartridge filters, addition of antiscalants (propriety chemicals), anti-biofoulants and antioxidants (sodium metabisulphite). Details of these are not included in the manuscript to provide brevity. All the membrane units have been designed to operate for 20 h a day with rest of the time provided for cleaning of membranes.

2.4. Analysis of physico-chemical parameters

Composite effluent samples collected from various stage of treatment in the plant were analyzed for various physico-chemical parameters such as pH, SS, TDS, COD, BOD, Cl^{-}, SO^{4-} and Na specifically for each stage of treatment. The parameters are chosen to indicate the critical pollutants present in the effluents and to evaluate the efficiency of each system. The major

Table 2
Pretreatment unit operations and processes implemented to meet influent quality for membrane treatment

Sequence of Pre-treatment

Treatment	C1	C2	C3	C4	C5	C6	C7	C8	
Design flow m^3/d	500	300	1200	500	500	750	500	500	
DB WW				50 450				36	464
Stage I	CP	CP	CP	CP	ASP	Ozonation	Electro coagulation	PESCO process	Electro coagulation
Operating conditions	Lime, ferrous sulphate/ferric chloride and polyelectrolyte at the dosing range between ● 150–400 mg l^{-1} ● 250–800 mg l^{-1} ● 50–150 mg l^{-1}, respectively				F/M = 0.01 d^{-1} MLSS = 3,500 mg l^{-1}	92% purity ozone contact time between 10 and 20 min or till the effluent colour intensity is reduced to a shade of light brown.	MSFRP reactors Blade type mild steel sacrificial electrodes, Flow – 25 m^3/hr, Rt – 25 minutes max.	MSFRP tank 120 nos titanium electrodes coated with tantalum & ruthedium, Rt – 60 minutes	Scour bath 36m^3d^{-1} treated effluent is fed along with wash water. Mild steel as sacrificial rods mesh type electrodes, Rt – 25 min
Stage II	SF + ACF	ASP	ASP	CP	Chlorination	ASP	SBR	–	CO-Oxy cell
Operating conditions	–	F/M = 0.05 d^{-1} MLSS = 3,000 mg l^{-1}	F/M = 0.03 d^{-1} MLSS = 3,500 mg l^{-1}	50–250, 100–450, 50–100 mg l^{-1}	200	F/M = 0.01 d^{-1} MLSS = 3500 mg l^{-1}	Rt = 8 h Se = 2 h MLSS = 4,000 mg l^{-1}	–	Titanium electrodes coated with tantalum & ruthedium, 107 nos electrodes
Stage III	–	SF + ACF	CP 75–200, 250–400, 25–75		DMF + ACF	PSF + ACF + IRF	CP	–	CP
Stage IV	–	–	SF + ACF	–	–	-	–	–	–

DB – Dyebath
WW – Wash water
CP – Chemical precipitation
SF – Sand filtration
DMR – Dual media filtration

ACF – Activated carbon filtration
ASP – Activated sludge process
SBR – Sequencing batch reactor
PESCO – Photosensitized electron mediating self generative chemical oxidation
MSFRP – Mild steel with fibre reinforced plastic coating

C0 – Catalytic oxidation
Rt – Reaction time
Se – Settle
IRF – Iron removal filter

Feed to membrane indicates adjustment of feed effluent quality to membrane by pH adjustment, solids removal through micron/cartridge filters, addition of antiscalants (propriety chemical), antibiofoulants and antioxidants (sodium metabisulphite). Details of these are not included to maintain brevity.

Table 3
Resource recovery module for water and salts from the treatment combination

Treatment sequence ↓

		Treatment combination									
Stages	Type	C1	C2	C3	C4		C5	C6	C7	C8	
1	Membrane type and material	– BWRO SW-PA	– BWRO SW-PA	– BWRO SW-PA	DB NF	WW BWRO-SW-PA	– BWRO-SW	– UF-HF	– BWRO-SW	DB UF	WW UF
	Feed pressure, PSI	285	250	285	120	180	300	115	180	60	60
2	Membrane type and material	SWRO SW-PA	SWRO SW-PA	BWRO SW-PA	–	BWRO SW-PA	SWRO SW-PA	SWRO SW-PA	SWRO SW-PA	NF	BWRO SW-PA
	Feed pressure, PSI	570	700	285	–	425	350	280	300	205	260
3	Membrane type and material	NF	–	SWRO SW-PA	–	SWRO SW-PA	SWRO SW-PA	SWRO SW-PA	PT- DM	–	SWRO SW-PA
	Feed pressure, PSI	200	–	610	–	470	450	400	800	–	570
4	Membrane type and material	–	–	–	–	NF	–	NF	–	–	UF
	Feed pressure, PSI	–	–	–	–	115	–	350	–	–	60
5	Membrane type and material	–	–	–	–	–	–	–	–	–	SWRO SW-PA
	Feed pressure, PSI	–	–	–	–	–	–	–	–	–	710
	Overall water recovery, %	65	72	90	89		80	83	91	92	

RO – Reverse osmosis	BWRO – Brackish water reverse osmosis membrane	SW – Spiral wound	PT - Plate tube
NF – Nanofiltration	SWRO – Sea water reverse osmosis membrane	HF – Hollow fibre	PSI – Pounds per square inch
UF – Ultrafiltration	PA – poly amide	DM - Disc membrane	

reason for selection of these parameters is they are critical to wastewater treatment, water reuse and salt recovery. Sodium chloride and sodium sulphate salts are used in the dyeing process and salt recovery means recovery of these salts. Chemical oxygen demand (COD) was determined by dichromate reflux. COD determinations were carried out with samples (10 ml each) which was centrifuged and filtered through 0.45 μm millipore filter. Analyses were done in duplicate for the same set of conditions. pH was determined in situ by pH meter (WTW multiline P4). The variations were systematically observed within ±5% of the stated values. All other pollutant parameters were analysed according to standard methods [18]. However, they are not presented here in the manuscript to improve clarity and intended to focus on the real pollutants. The chemical reagents and standards were of Merck India Ltd. and were of analytical grade.

2.5. Sample collection and effluent characteristics

Three rounds of monitoring were undertaken in the textile cluster. Each round of sampling is for seven days and not necessarily in sequence so as to fit into the scheme of textile process. Most of these units undertake work on job order basis for European and American clients. Each round of monitoring includes collection of hourly composited samples during the operational hours of the ETP. The effluent samples collected were analysed for the aforereferred parameters at each stage of effluent treatment (Table 4). The physico-chemical characteristics of the effluents indicated high concentrations of pollutants attributed to textile processing viz., colour, solids, BOD, COD and salts. The overall range of raw effluent characteristics from the units indicated a biodegradable nature. The pH of the samples were mostly alkaline with a range between 6.5 and 11.0.

2.6. Cost estimate of treatment options implemented ZLD

The major objective of the study was assessment of the cost estimates of the technological options implemented for ZLD. Acquisition of an advanced technology can enhance the treatment quality and recover valuable products. However, entails high budgetary commitments, which may force administrators to make decisions of new technologies with clear evidence on its effectiveness, economic advantages and clinical utility of the technology. Under such circumstances, costing of the technologies becomes utmost importance in major decision-making processes. Judgment can be made based on the cost associated with the treatment options. Secondary data of the financial details were obtained from the member industries through the study. The major criterion adapted for costing of the technology were capital (Eq. (1)) and operations and maintenance (OM) costs (Eq. (2)), performance removal of major pollutant parameters, recovery, sludge and reject handling costs.

$$TCc = Cc + Mc + Elc, \tag{1}$$

where TCc is total annualized capital cost, US \$. Cc is civil works, US \$. Mc is mechanical equipments cost, US \$. Elc is electrical equipments cost US \$.

$$\mathrm{OMc} = \mathrm{MPc} + \mathrm{CHc} + \mathrm{EPc} + \mathrm{SRc} \tag{2}$$

where OMc is total operation and maintenance cost, US \$. MPc is manpower costs, US \$. CHc is chemical consumption cost, US \$. EPc is electric power cost, US \$. SRc is sludge and reject handling costs, US \$.

3. Results and discussions

The studies have proved that a combination of UO&P s are required to meet the effluent quality required to meet the regulatory norms of discharge. Comparison of technologies available in the market was necessary to assess the amount required for investment in the treatment system. This exercise was required as most of the textile units are small and medium scale and could not afford expensive treatment systems to meet regulatory norms. The success of any technology for wastewater management depends upon various criteria, which acts for and against the acceptability of the processes involved. Comparisons of the technology options have been made with respect to major criteria for ranking. All the membrane units were designed to operate only for 20 h a day to provide time to enable membrane cleaning. The pretreatment schemes have been designed to run throughout the day under maximum load. All the units are designed to handle wastewater for maximum flow, however, during the assessment period the lower inflows were observed.

3.1. Quality of the effluents in the treatment

The characteristics of treated effluent from each treatment option has been analysed at various stages of treatment and is presented from Table 4. Broadly three major parameters were considered for pretreatment up to tertiary stage which included suspended solids, biochemical oxygen demand and chemical oxygen demand (Fig. 1). It was observed that in conventional treatment (C2, C3 and C4) a reduction was achieved for suspended solids, BOD and COD at the rate of 84.4%, 85.5% and 81.1%, respectively. However, with respect to advanced treatments only combination

Table 4
Effluent characteristics from treatment combinations 1 to 8

		Effluent quality, mg l^{-1}			
Options	Parameters	Raw effluent	Pretreatment	Advanced treatment (RO permeates)	Membrane rejects to evaporation pans
1	SS	190–260	114–144	NIL	374-520
	TDS	9,582–10,714	10,638–11,732	650-725	33030-37785
	COD	380–529	242–370	68 – 80	557-900
	BOD	100–105	40–50	10-15	135-198
	Cl^{-}	4,855–5,806	5,010–5,716	900-985	18118-19832
	SO^{4-}	819–1,160	868–1,220	212-300	2305-3308
	Na	760–820	790–835	150-220	2668-2785
2	SS	430–520	70–85	NIL	210-346
	TDS	4,552–5,980	4,672–5,824	344-460	32105-43820
	COD	711–860	117–156	NIL	420-570
	BOD	305–368	32–80	NIL	98-134
	Cl^{-}	2,210–3,354	1,984–3,254	158-210	13104-34799
	SO^{4-}	609–698	718–804	100-142	4410-8740
	Na	1,493–1,605	1,456–1,624	174-200	9210-9440
3	SS	214–232	12–16	ND	48-120
	TDS	4,535–4,820	4,540–5,380	380-410	39836-61462
	COD	880–1,075	176–194	ND-35	820-2156
	BOD	290–372	34–44	ND-6	234-568
	Cl^{-}	85–100	94–242	60-80	568-2816
	SO^{4-}	2,700–2,800	2,110–2,123	142-178	18669-24454
	Na	1,050–1,475	1,370–1,718	130-150	12070-19728

Table 4
contd...

Combination 4		Wash water effluent				
	Parameters	Raw effluent	Three stage chemical precipitation	Two two stage RO permeates	Third stage Ro feed or two-two stage RO rejects	Third stage RO rejects to evaporator
	SS	1,982–2,100	128–160	ND–10	225	425–450
	TDS	6,200–6,580	6,980–7,120	294–320	30,150–37,550	59,800–74,760
	COD	875–1,133	242–370	ND	542–730	998–1,460
	BOD	328–333	70–97	ND	118–170	194–334
	Cl^{-}	712–950	752–1,820	62–72	3,395–5,930	6695–11,720
	SO^{4-}	1,814–2,670	1,742–2,575	50–142	6,910–9,560	13,672–18,980
	Na	1,180–1,540	858–1,445	42–88	2,910–6,360	5,725–12,638
		Dye bath effluent				
	Parameters	Raw effluent	Single stage chemical precipitation		Two stage NF permeates	NF rejects to evaporator
	SS	350–390	210–262		ND–45	210–475
	TDS	16,844–17,410	16,290–17,698		7,235–9,075	36,188–39,620
	COD	1,013–1,250	665–884		224–548	1,535–1,818
	BOD	364–375	219–225		66–135	430–458
	Cl^{-}	3,980–4,125	4,258–4,410		1,492–2,595	9,435–10,175
	SO^{4-}	3,570–3,820	3,628–3,995		1,255–2,220	8,727–8,908
	Na	3,200–3,220	3,010–3,180		1,298–1,872	6,234–9,818

Table 4
contd. . .

Combination 5	Parameters	Raw effluent	Activated sludge process (ASP)		3-stage RO permeate	Ro reject to evaporator
	SS	405–450	225–270		NIL	282–482
	TDS	6,745–6,920	6425–6680		350–355	30,224–31,645
	COD	371–1,120	148–516		NIL	506–1,974
	BOD	126–380	45–178		NIL	282–480
	Cl^-	880–961	855–904		85–90	3,615–3,920
	SO^{4-}	1,748–1,840	1724–1805		120–132	7,980–8540
	Na	920–1,000	820–982		60–64	3,606–4,274
Combination 6	Parameters	Raw effluent	Ozonation	ASP	Combined RO permeate	RO reject to evaporator
	SS	172–355	150–284	105–156	NIL	620–1,320
	TDS	5,195–5,650	5,018–5,480	4,860–5,314	325–428	57,690–62,032
	COD	495–633	312–380	190–218	NIL	1,024–2,822
	BOD	143–200	80–110	48–50	NIL	178–182
	Cl^-	2,270–2,376	2,120–2,180	2,045–2,110	102–182	23,378–46,014
	SO^{4-}	422–480	285–370	236–320	52–85	2,330–4,136
	Na	68–80	55–75	51–70	26–30	264–1,178
Combination 7	Parameters	Raw effluent	Electro coagulation	SBR	Combined RO permeate	RO reject to evaporator
	SS	120–135	84–100	52–90	NIL	160-378
	TDS	4220–4610	4,165–4,460	4,130–4,420	230–270	38290-49340
	COD	672–840	564–592	282–384	NIL	1844-2592
	BOD	222–294	180–186	84–104	NIL	236-710
	Cl^-	1135–1589	1,120–1,568	1,108–1,539	56–72	12694-13708
	SO^{4-}	340–486	328–472	315–443	44–46	3018-6254
	Na	345–500	330–484	310–462	42–72	2848-3092
Combination 8	Parameters					
	Wash water stream		Raw effluent	Catalytic oxidation-chemical precipitation	UF permeate	Four stage RO permeate
	SS		50–68	20–30	25–30	ND
	TDS		5,858–6,445	5,520–6,196	5,302–5,430	350–375
	COD		1,420–1,673	1,100–1,323	692–720	ND
	BOD		75–85	56–65	70–98	ND
	Cl^-		1,520–1,747	1,405–1,648	985–1,092	115–130
	SO^{4-}		350–480	320–453	145–245	68–88
	Na		960–1,008	800–942	150–245	45–52
	Dye bath stream			Electro-coagulation & precipitation	NF permeates	NF rejects to evaporator
	SS		520–620	10–15	ND	180–192
	TDS		40,380–45,250	36,375–41,280	17,380–22552	30,300–32,300
	COD		2,280–2,520	480–980	305–450	1,346–1,486
	BOD		550–580	100–105	38–66	210–250
	Cl^-		20,120–21,220	18,220–18,885	11,478–18,860	17,520–19,250
	SO^{4-}		9,210–9,426	7,882–8,880	4,650–8,870	9,050–9,425
	Na		4,830–5,382	4,840–5,120	3,174–4,230	3,056–7,250

C6 could meet above 80% removal of SS, BOD and COD. Additionally, C6 was easier to operate with the operators by simply increasing the ozone concentration in the pretreatment during higher COD loads whereas; C7 and C8 had difficulties in the operation such as controlling the electro-coagulation and electro-oxidation.

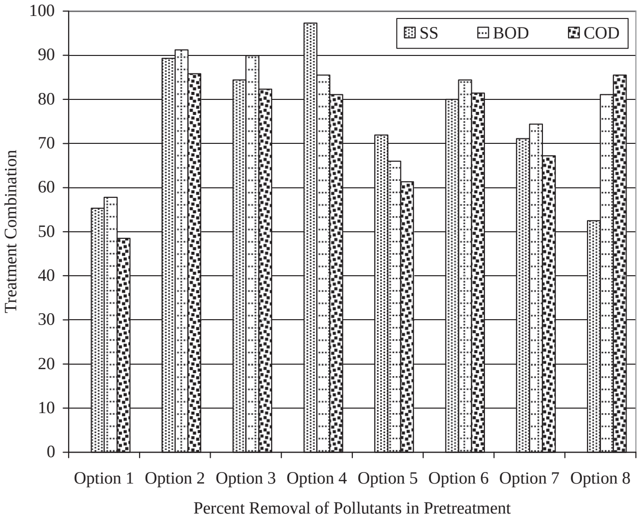

Fig. 1. Percent reduction of pollutants in pretreatment for water recovery through membrane systems.

Higher concentrations of suspended material impacted the performance of C7 & C8 vis-à-vis C6. Also another reason observed was recent implementation of advanced treatments in the cluster and the wisdom gained in operation of conventional treatments for long to meet the regulatory norms. C8 performed consistently with respect to BOD and COD reduction in the pretreatment, however with higher operating costs among the entire pretreatment module (2.08m^{-3}). C3 could match similar pollutant removal efficiencies, operating costs (1.50m^{-3}) and water recovery but additionally with sand filtration and activated carbon adsorption processes.

3.2. Effectiveness of capital investment

The choice of the treatment combination depends upon the initial investments required for the implementation of the technologies which further increases the capital cost of treatment (Fig. 2). The capital cost in the case of C3, C5 and C6 (0.76, 0.69, 0.66 Million US$) were high vis-à-vis other treatment combinations due to installation of aerobic biological treatment (activated sludge processes in extended aeration mode). However, C2 exhibited lower capital cost vis-à-vis C3, C5 and C6 owing to simpler pre and advanced treatment. Unit wastewater treatment cost of all biological treatment units varied from 648.56 to 1383.33 US $ per cubic meter of wastewater treated with the highest treatment cost observed in C5 and C7. C3 capital cost of was higher due to large quantity of water to be treated (1,200 m^3/d) than all the other treatment combinations which offset higher foot print for the chemical and biological treatment. Another aspect of this scheme is the unit capital costs are higher for advanced treatment schemes (C5, C7 and C8) except for the treatment combination C6 (ozonation and biooxidation) due to higher levels of automation and safety requirement. The increase in total capital cost and unit treatment cost rose proportionally across the treatment combinations. The data reveal that there is very low influence of benefits from low foot print, shorter reaction and residence times of the advanced treatment combinations. The capital costs presented is higher for similar scale of industry operated in the same region which could be due to increase in civil costs [5,16].

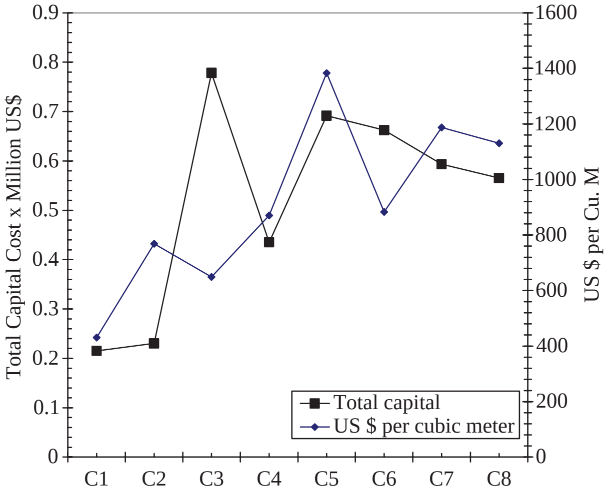

Fig. 2. Trend of capital cost and unit capital cost of the combinations.

The total capital cost invested for treatment is split between pretreatment, advanced membrane treatment and rejects management (Fig. 3). The capital cost of

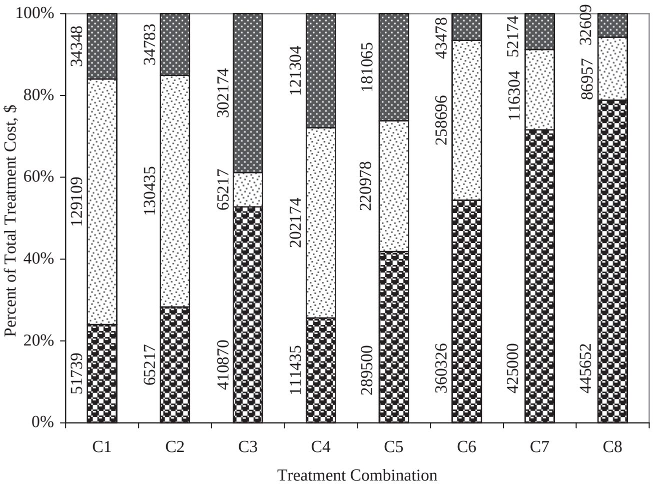

Fig. 3. Percent capital contribution of pretreatment module, advanced and reject management.

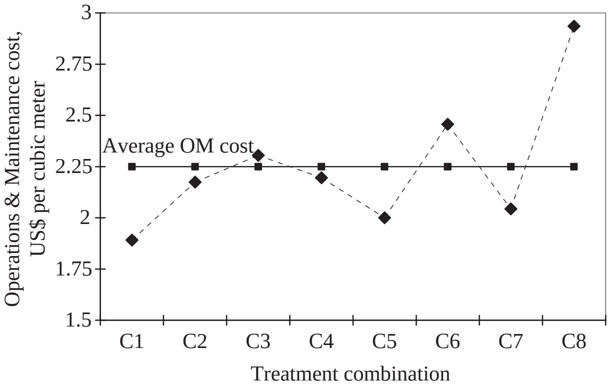

Fig. 4. Operational costs across the treatment options.

pretreatment options based only on chemical treatment (C1 and C4) ranged between 25% and 28% of the total cost invested. An increment in capital cost was observed with addition of biological treatment to the chemical treatment from 29% to 52% (C2, C3 and C5). Pretreatment capital cost went above 75% for investment in advanced oxidation processes prior to membrane application. The reasons are obvious due to import of technology, components and spares. A trend was observed based on the graph (Fig. 3), indicating reduction in capital contribution from membrane systems and rejects management as advanced technologies were adopted. However, this observation has to be read alongside Fig. 2 which presents the total and unit capital cost of the treatment combination.

3.3. Role of operations and maintenance in the treatment options

The cost of operating the treatment options involves cost towards the treatment (Eq. (2). The total operation and maintenance costs varied between 1.89 and 2.94 US$ (Fig. 4). The average cost of textile effluent management in the region mounted to 2.25 US$ per cubic meters of wastewater treated. The total operation and maintenance costs have not increased from 1.79 to 1.89 US$ per cubic meter of wastewater treated in the same region for a study conducted few years earlier [5,16]. The OM cost was observed to be significant parameter for selection of the pretreatment combination in the cluster. C3, C4, C5 and C7 whose OM costs were less than average (2.25 $\$m^{-3}$) was mostly preferred and installed with other criteria for selection of pretreatment module such as pollutant removal, water recovery and capital costs on par. However, the increased operating costs conducted in the earlier studies were limited to conventional treatment of physico-chemical treatment and biological treatment. The increased costs are as a result of increased demand from various industries opting for advanced technology in the region. The conventional treatment costs were similar even with rise in the cost of chemical and power cost during the half decade. The major reasons attributed by the vendors and industrial units is increased availability of membranes and lower costs due to reduced duties of imported components on the zero effluent liquid discharge systems. The total cost of treatment of the zero discharge schemes is worked out and is presented in Table 5.

3.4. Water recovery vs operation and maintenance

The study has underlined utmost importance for proper operation and maintenance of the equipment used in process. The level of importance to the effluent treatment provided by the industries has been correlated through the average expenditure incurred in the operation and maintenance of the treatment system during the period under consideration. Higher water recovery was obtained at higher OM cost. The average water recovery of 85% was observed with a recovery range between 65% and 92% (Fig. 5). Except for combination 1 and 2 other 6 combinations provided a water recovery above 80% which is higher in comparison to effluent recycling undertaken in another region [18]. Water recovery in C3, C4, C7 and C8 was about 90%. However, based on plant operator's experience, segregated treatment presented a problem by itself. Advanced pretreatment processes such as electrocoagulation, catalytic oxidation provided higher water recovery at the rate of 90% vis-à-vis conventional textile effluent treatment (chemical precipitation, C3 and C4). However, the recovery was achieved with increasing osmotic pressures and membrane stages (C7 and C8). Membrane cleaning was periodically undertaken to reduce membrane fouling when there is a reduction of permeate design flow by 10%.

3.5. Impact of the treatment on recovery of sodium brine and salts

Nanofiltration is used for selective separation of sodium salts present in the dye bath and wash waters for salt recovery in the treatment options. The concentration of the sodium salts is raised during the incremental reverse osmosis stages. The feed to the nanofiltration consists of concentrated RO rejects, which contains monovalent, divalent and trivalent salts carried over from membrane separation of the effluent. Nanofiltration membranes specifically pass monovalent ions such as sodium and reject divalent ions such as calcium, magnesium, etc. The NF

Table 5
Cost implication of the ZLD operation from the treatment combination

		Expenditure							
Effective operation costs		C1	C2	C3	C4	C5	C6	C7	C8
Operational flow, m^3.d^{-1}		110	450	1200	500	500	330	335	275
Total cost of treatment (Expenditure), $.		208.04	978.26	2765.22	1097.83	1000.00	810.65	684.57	807.07
Total cost of treatment (Expenditure), \$.m^{-3}		1.89	2.17	2.30	2.2.	2.00	2.46	2.04	2.93
Recovered water (% recovery from membrane treatment @ of 0.87\$/m^3)		0.65 62.17	0.72 281.74	0.9 939.13	0.89 386.96	0.8 347.83	0.83 238.17	0.91 265.09	0.92 220.00
Condensate (water produced from evaporator operation)		–	–	62.09	58.70	68.87	37.39	21.13	26.09
Salt savings (sodium sulphate @ 0.1$/kg of salt recovered or sodium chloride brine for process reuse)	Recovery	Nacl 19.09	Nacl 14.46	$NaSO_4$ 29.17	$NaSO_4$ 10.70	$NaSO_4$ 84.78	$NaSO_4$ 32.780	$NaSO_4$ 19.20	NaCl 14.24
Effective cost expenditure, $.		126.78	682.07	1796.91	700.17	567.39	539.70	400.28	572.83
Net cost of treatment, \$.m^{-3}		1.15	1.52	1.50	1.40	1.13	1.64	1.19	2.08

Intangible benefits which could not be monetizatied include savings from non-installation of ion change resins for softening of fresh water, cost of fresh water, assured supply of water during lean months, prevention of pollution of the environment through least discharge, first shot acceptance of dyed cloth by vendors in comparison to fresh water use, lower time required for dye colour and shade testing.
One US dollar ($) = ~46 Indian Rupees (Rs.) as on 2009.

permeate ($NaSO_4$) is concentrated in evaporator and then crystallized for reuse in the process. If the salt used in the process is sodium chloride than the brine from nanofiltration is directly used in dyeing process. If the salt used is sodium sulphate, the permeate is evaporated and salt recovered for process reuse. The nanofiltration systems are designed to recover maximum sodium brine from the RO rejects. Based on the monitoring, salt recovery from NF ranged between 30% and 55% of the feed salt present in the raw effluent. The reduction in net cost of the treatment recovering sodium chloride salts ranged between 29.02% and 39.06% (average 32.7%), and sodium sulphate salt between 35.02% and 43.26% (average 37.89). Based on the studies, a reduction in consumption of fresh primary salt (sodium sulphate) in the dyeing section for process use was reduced up to a maximum of 65% under optimum working conditions of the plant. The major benefits as indicated by the industrial units include non-softening of procured freshwater and better dyeing. The total cost of treatment of the zero discharge schemes is worked out as presented in Table 5.

4. Conclusion

ZLD has become an essential regulatory requirement for textile wastewater management in many parts of the world due to its long and short term impacts on the water environment. To meet this criterion, textile effluents require quintessentially a sequence of treatment options to recover water and salts from the effluent streams and reduce the discharge to the environment. Due to stringent pollution control norms on discharge, waste minimization and scarcity of water, the textile units have to find a suitable option for recovery of chemicals and water without damaging the surrounding environment. This case study has thrown a large possibility of treatment options to meet the major objective of ZLD. Caution is required before installation of any new technology with knowledge

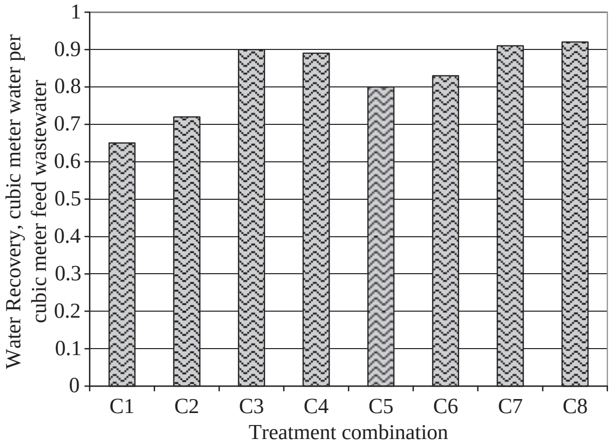

Fig. 5. Water recovery across the treatment options.

on the cost benefits associated with the technology. However, success of any treatment technology is the intersection of the requirements of concerned stakeholders such as industry, regulatory bodies, vendors and public. Recent developments in advanced oxidation processes and membrane technologies provides an opportunity to cut down treatment cost by recovery of raw materials in the form of chemicals from the waste stream which otherwise may prove expensive, if water only is recovered. The most important limitation in textile wastewater treatment by membrane processes is fouling which causes a rapid flux decline. Pre-treatment is an important component in the membrane selection and operation. This study provides an understanding of various treatment options and the likely recovery of resources such as water and chemicals along with some intangible benefits which promotes sustainable development. Time has reached to utilise the benefits of membrane systems for desalination and water treatment in developing countries prone to water scarcity and industrial water pollution.

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