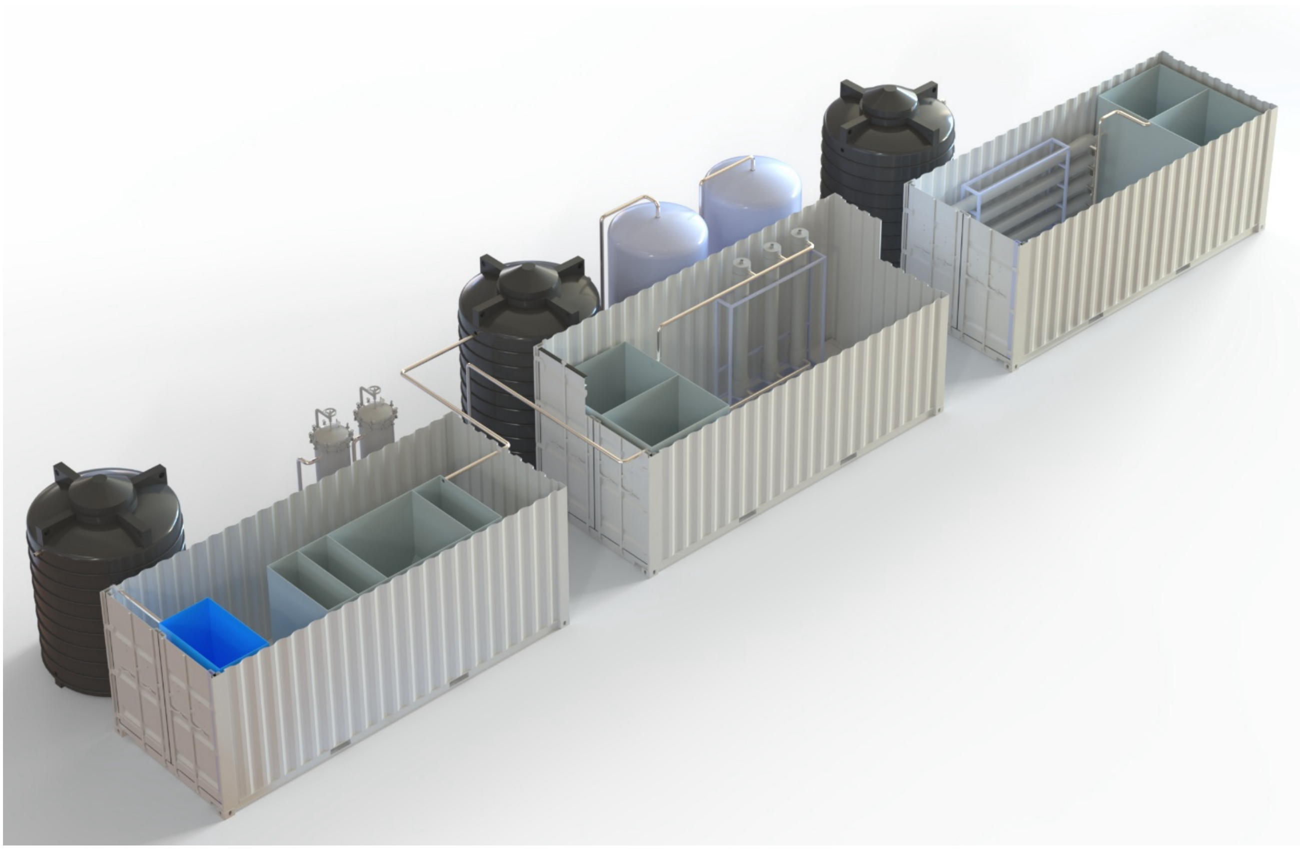
Sustainable Manufacturing and Environmental Pollution Programme:

PILOT DEMONSTRATION OF WATER RECYCLINGFOR THE TEXTILE INDUSTRY

Detailed technical report



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SMEP | Sustainable Manufacturing and Environmental Pollution Programme
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Executive Summary

The SMEP[1] pilot was designed to test whether textile wastewater that had already passed through a conventional effluent treatment plant could be recycled back to production at materially meaningful recovery levels. The stated design ambition was to recover up to 80% of ETP-treated water, while also generating a defendable understanding of what happens to the remaining reject stream and what treatment additions are required to comply with ZDHC (Zero Discharge of Hazardous Chemicals) progressive limit for the remaining discharge.

The pilot confirmed a central lesson that is often understated in vendor-led recycling discussions: generating high-quality permeate is not the hardest part of the system. The harder task is managing the concentrated reject. The pilot produced excellent reverse-osmosis permeate in both tested sectors, but the reject stream became the focal point for cost, process complexity, and compliance risk. This was most evident in reactive dyeing wastewater, where residual color and high dissolved solids persisted after membrane concentration and required a dedicated polishing step.

The pilot also demonstrated that textile wastewater cannot be treated as a single category. Wastewater from reactive dyeing behaved fundamentally differently from wastewater from denim washing. In reactive dyeing, recovery was constrained to roughly 60-70% under the observed operating conditions because high TDS and high color increased membrane pressure requirements and intensified reject management difficulty. In denim washing, by contrast, the lower TDS and more colloidal nature of the pollution load allowed more than 80% water recovery and avoided the need for polishing oxidation in the presented trials.

Economically, the pilot materials suggest that partial recycle systems are materially more accessible than conventional ZLD systems, especially for easier wastewater segments. Indicative full-scale economics for a 100 m3/h plant were presented at about USD 0.30/m3 for reactive dyeing under a 70% recycle / 30% discharge case, compared with about USD 2.2/m3 for

[1] The UK Government funds this research and pilot activity through UK International Development; however, the views expressed do not necessarily reflect the UK Government's official policies. The grant has been provided through the Sustainable Manufacturing and Environmental Pollution Programme (SMEP). The SMEP programme is funded by the UK Government and implemented in partnership with UN Trade and Development (UNCTAD). The grant has been awarded from Feb 2024 to Feb 2026. More information visit: www.smepprogramme.org

conventional ZLD. That step-change underscores why the future of cost-effective circularity lies not only in adding more RO stages, but in fundamentally rethinking brine management.

The project therefore framed the next phase as a reject-management problem: how to concentrate, purify, and recover salt without relying so heavily on thermal evaporation. The proposed multimembrane route - combining further concentration with membrane-based salt separation and only a small residual evaporative tail - remains conceptual, but it is directionally consistent with the pilot evidence. If successful, it could sharply reduce both OPEX and CAPEX compared with conventional MEE-ATFD-based ZLD.

Item	Pilot finding
Feed boundary	Secondary / ETP-treated textile wastewater; pilot intake about 5 m3/h in the presented examples.
Core process train	Bag or pre-filter -> UF -> two-stage RO -> reject treatment using EC, DAF, sand filtration; polishing oxidation added where needed.
Observed recycled water quality	RO permeate was essentially color-free with TDS around or below 100 mg/L in both tested sectors.
Observed recovery	Reactive dyeing: about 60%; denim washing: about 80% or slightly higher in the presented case.
Primary technical bottleneck	Brine / reject management, especially for high-TDS reactive dyeing wastewater.
Critical learning	Electrocoagulation alone was insufficient to remove refractory color in reactive dyeing reject; polishing oxidation was needed.
Economic implication	A 70% recycle system appears far more affordable than conventional ZLD; thermal ZLD cost is dominated by evaporation and drying.

Item	Pilot finding
Scale-up priority	Pilot the proposed multimembrane brine purification route and localize operations and maintenance capability.

Abbreviations

Term	Meaning
AOP	Advanced oxidation process
ASP	Activated sludge process
ATFD	Agitated thin film dryer
BOD5	Five-day biochemical oxygen demand
CAPEX	Capital expenditure
CIP	Clean-in-place
COD	Chemical oxygen demand
DAF	Dissolved air flotation
EC	Electrocoagulation
ETP	Effluent treatment plant
MEE	Multiple effect evaporator
NF	Nanofiltration
OPEX	Operating expenditure
RO	Reverse osmosis
SDI	Silt density index
TDS	Total dissolved solids
TSS	Total suspended solids
UF	Ultrafiltration
ZDHC	Zero Discharge of Hazardous Chemicals
ZLD	Zero liquid discharge

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1 Context and purpose

The SMEP project framed textile wastewater recycling as both an environmental necessity and an industrial transformation challenge. In the Bangladesh context, factories face rising pressure to reduce freshwater consumption, meet discharge standards more consistently, and respond to buyer expectations around circularity. At the same time, recycling technologies remain capital intensive, technically demanding, and heavily dependent on imported equipment and foreign service support.

The pilot was therefore positioned as a de-risking instrument. Rather than claiming a universal solution, it sought to demonstrate the treatment envelope of a modular system and to generate operational evidence under different wastewater conditions. The immediate objective was to demonstrate up to 80 percent recycling of ETP-treated effluent together with an appropriate reject-management strategy. The deeper objective was to identify which industrial segments are most ready for scale-up and which technical barriers still need to be resolved before wider adoption can be justified.

This report retains that framing. It interprets the pilot not simply as a treatment train, but as an evidence-building exercise for investment decisions, technology localization, and future zero-liquid-discharge pathways.

Why pilot demonstrations matter in this context

- They reveal how recovery changes when feed TDS, COD, and color vary across textile segments.
- They help distinguish between what is technically feasible in principle and what is financially viable in practice.
- They show where the treatment bottleneck sits—in this case, mainly in reject management rather than permeate quality.
- They provide a basis for more realistic performance guarantees and scale-up decisions.

2 Industry challenges and rationale for piloting

The pilot was conceived against a backdrop of structural barriers that are common across textile clusters but particularly acute where membrane recycling remains a relatively new practice. The project explicitly identified lack of local technical know-how, high import duties on recycling equipment, high investment cost, high operating cost, weak access to continuous after-sales support, and a heavy dependence on foreign suppliers. Together, these constraints create a market failure: although water recycling is increasingly necessary, factories often do not have the confidence or local ecosystem needed to deploy and sustain it.

Pilot Containers

The project made clear that these barriers are not abstract. The operations team initially found the pilot difficult to understand and operate. That early difficulty is important, because it illustrates why seemingly simple statements such as "install UF and RO" often understate what it takes to run a stable recycling plant. Chemical dosing, cleaning strategies, membrane choice, RO reject handling, and the day-to-day interpretation of varying wastewater quality all require operational capability, not just equipment procurement.

Another barrier is institutional. The project contrasted the local context with cases where governments helped finance the transition to ZLD. Without such support, factories judge recycling systems primarily on direct financial return and immediate operating burden. In that environment, underperforming vendors promise to have a long shadow. A pilot therefore becomes a credibility tool as much as a technical tool: it allows the treatment logic to be demonstrated under recognizable operating conditions and reveals where promised performance does or does not hold.

Barrier	How it identified in the project	Why it matters technically	Implication for scale-up
Limited local expertise	Factories rely on foreign providers for design advice and troubleshooting.	Membrane systems are sensitive to feed quality, cleaning, SDI, scaling, and recovery control.	Need for local operators, service teams, and standard operating procedures.
High import tax and CAPEX	Membrane and treatment equipment were described as heavily taxed and expensive.	Raises cost threshold for piloting and for full-scale rollout.	Factories seek high certainty before investing.
High OPEX	Energy, chemicals, and reject management were emphasized repeatedly.	Cost rises sharply with TDS and with thermal evaporation.	Design should optimize around recovery where economics still make sense.
Weak after-sales support	Continuous technical service is difficult to secure locally.	Unstable systems can drift quickly without specialist support.	Localization of service is essential for bankable deployment.
Performance skepticism	Factories reported prior disappointment when systems failed to meet promises.	Over-optimistic recovery claims can hide reject management or polishing burdens.	Pilot validation should precede large procurements.
Lack of incentives	Factories face the full cost of transition in the absence of strong policy support.	Projects compete against other capital priorities.	Donor and policy instruments can improve adoption economics.

Why a pilot was justified

The project explicitly framed the pilot as a process-optimization exercise. In other words, if every step and result had been fully known in advance, a pilot would not have been necessary. The fact that polishing oxidation and an extra UF or Sand Filter emerged as important lessons is evidence that the pilot fulfilled its intended role.

3 Textile wastewater typology and its implications

A major contribution of the pilot is that it treats textile wastewater as segment-specific rather than generic. From Bangladesh perspective, wet-processing universe is divided into three broad groups: reactive dyeing (woven and knit), denim and twill washing, and sweater washing. This segmentation matters because the economics and unit process requirements are driven less by abstract sector labels and more by concrete water quality parameters such as TDS, COD, color, colloidal load, and reject-handling burden.

Reactive dyeing wastewater is the most difficult case because it combines high dissolved salts with strong color and significant organics. Those characteristics increase osmotic pressure, reduce practical recovery, intensify scaling risk, and create a darker, more chemically resistant reject stream. In contrast, denim washing wastewater was described as having lower TDS, moderate COD, and much less persistent color. It is also evident from the pilot that much of the pollutant burden in denim washing is colloidal, which explains why ultrafiltration yields a visibly larger improvement than in reactive dyeing.

Sweater washing was identified as lightly polluted and easy to treat, but the slide deck did not present a pilot data set equivalent to the reactive and denim cases. Accordingly, the report treats sweater washing as an indicative low-difficulty segment in economics discussion rather than a validated pilot result.

Segment	Typical quality signal	Main treatment challenge	Practical recovery implication	Likely additional requirement
Reactive dyeing (knit / woven)	High TDS, high COD, high color; reject becomes dark and concentrated.	Low recoverability at a given membrane pressure; refractory color in reject-treatment train.	About 60-70% under presented operating conditions.	Polishing oxidation for refractory color / COD and careful brine management.
Denim and twill washing	Moderate COD, lower TDS (~1,000 mg/L), much lower color; pollutants more colloidal.	Front-end solids/colloid management rather than extreme	Around or above 80% in the presented case.	EC-DAF-sand filter sufficient for reject-treatment in presented trials.

Segment	Typical quality signal	Main treatment challenge	Practical recovery implication	Likely additional requirement
		dissolved-salt control.		
Sweater washing	Lightly polluted, little or no color, easier biological treatment.	Main challenge is usually economic justification rather than technical difficulty.	Potentially high, but no pilot result presented in detail.	Simpler polishing train; case-specific economics.

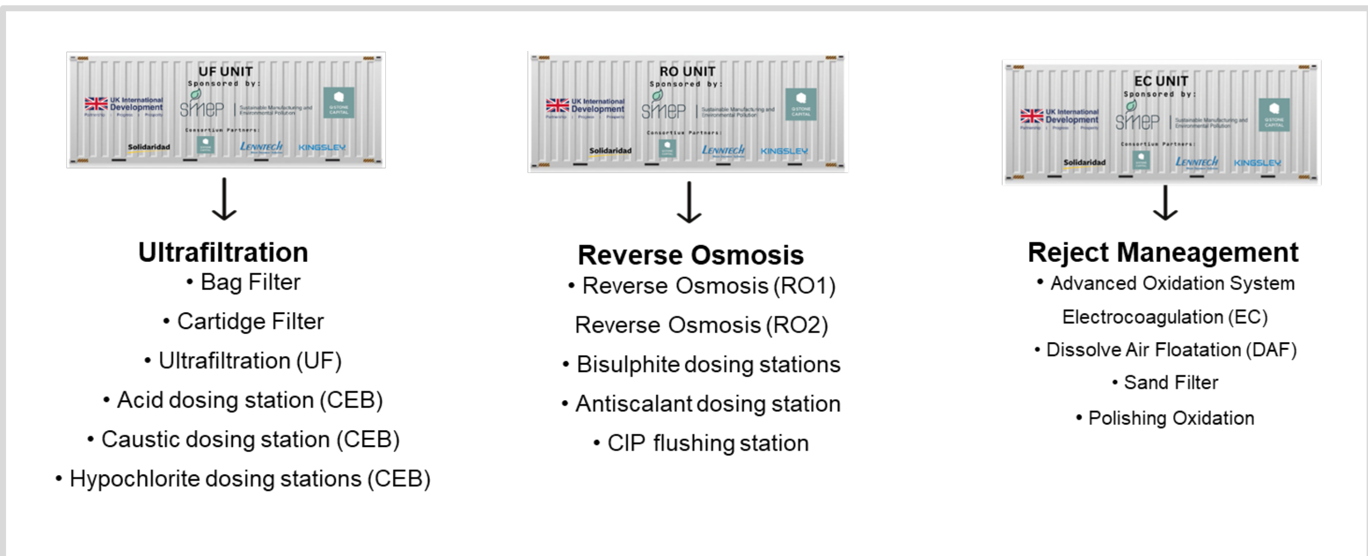
4 Pilot system architecture, process train, and operating envelope

The pilot is a modular, movable system assembled in three 20-foot containers. The stated design target was to recycle up to 80% of ETP-treated water, but the project repeatedly stressed that this is a conditional target rather than a universal result. The actual recovery that can be achieved depends on the textile segment and, above all, on the feed TDS that reaches the membrane train.

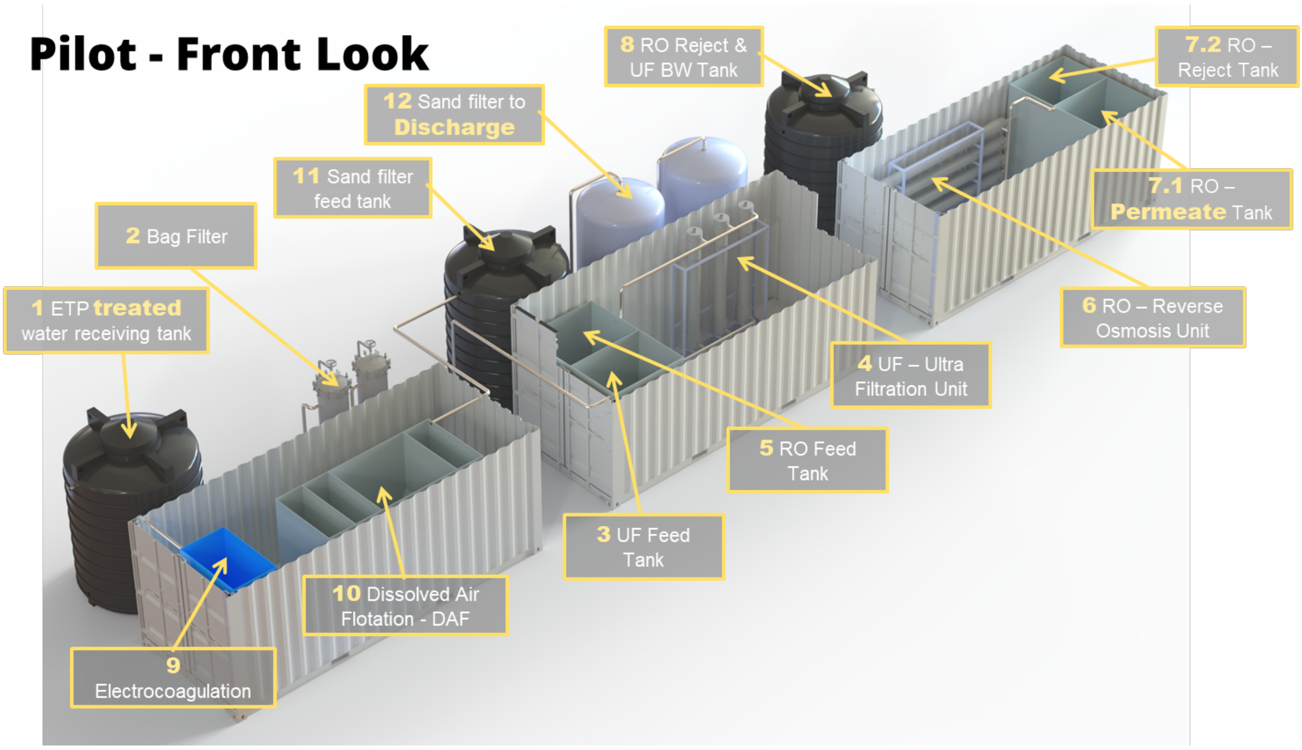
The process sequence begins after secondary treatment. ETP effluent is first received in a dedicated tank and then passed through pre-filtration before ultrafiltration. The UF step does not primarily remove dissolved pollutants; its role is to protect the RO system by removing suspended matter and lowering feed turbidity and SDI. UF filtrate then feeds a two-stage RO system, which produces the recycle water stream and a concentrated reject stream. The reject, together with UF backwash, is directed to a separate management train that includes electrocoagulation, dissolved air flotation, and sand filtration. For reactive dyeing wastewater, the pilot concluded that this train still leaves a refractory color fraction, requiring polishing oxidation as an extra step.

The project referred to the reject-treatment module as an "advanced oxidation" unit, constituted with a reject-management train with electrocoagulation and solids-liquid separation as DAF. This distinction matters because electrocoagulation is not the same as polishing oxidation. The first destabilizes and removes particulate and some dissolved contaminants; the second is specifically aimed at the refractory color and COD that remain chemically resistant after EC and DAF.

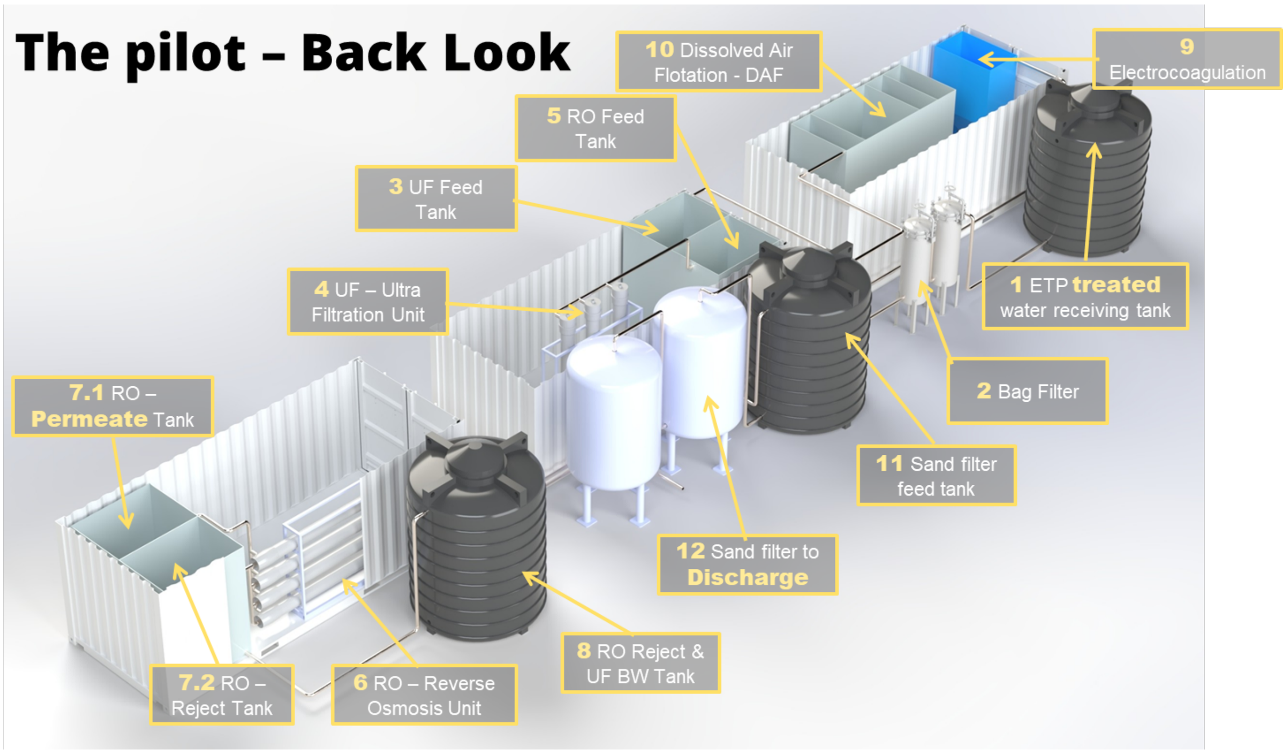
Module	Main equipment named for the pilot	Primary function	Key design note
Module 1: front-end conditioning and UF	Receiving tank, bag filter, cartridge filter, UF, dosing station, cleaning station.	Remove suspended solids, protect downstream membranes, produce stable UF filtrate for RO.	UF mainly improves TSS and feed stability; it does not materially reduce TDS or color in reactive dyeing.
Module 2: two-stage RO	RO feed tank, Stage-1 RO, Stage-2 RO, permeate tank, reject tank.	Produce low-TDS recycle water and concentrate dissolved pollutants into reject.	The two-stage arrangement improves overall water recovery but becomes sensitive to TDS and scaling risk.
Module 3: reject management and finishing	Reject/backwash tank, electrocoagulation, DAF, sand filter, optional polishing oxidation.	Treat the concentrated reject and backwash stream for discharge or further management.	Reactive dyeing required an added polishing oxidation step; denim washing did not.



Pilot modules and principal equipment



Pilot - front look



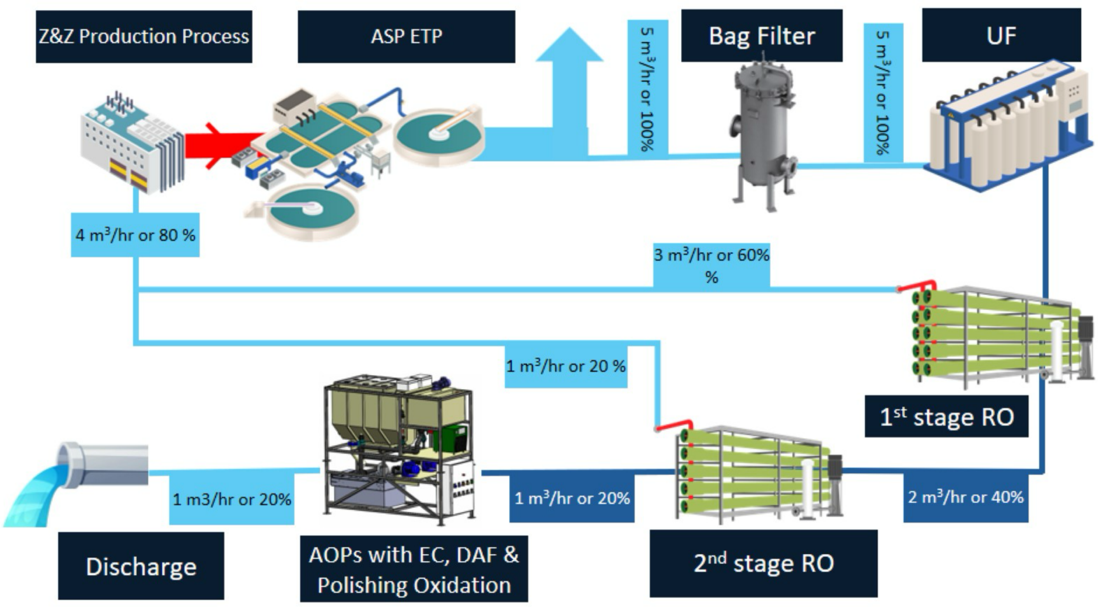
Pilot - back look

4.1 Operating envelope and observed limitations of the Pilot

The pilot has several limitations that are critical to interpreting the results. First, the pilot was optimized to understand treatment behavior, not to represent full-scale economics. Pilot OPEX can therefore look significantly higher than scaled-plant OPEX because a small system does not enjoy the same membrane area utilization, pumping efficiency, chemical optimization, or labor distribution as a full-scale installation.

Second, the pilot was designed to perform best around a feed TDS of roughly 2,000-2,500 mg/L. As feed TDS rises beyond that level, recovery declines. The project specifically identified that the system had been designed around approximately 2,500 mg/L TDS and that recovery would drop when the feed exceeded roughly 2,000 mg/L and especially when it exceeded 2,500 mg/L. This is a crucial constraint for interpreting why reactive dyeing stalled around 60-70% recovery while denim washing exceeded 80%.

Third, the pilot required adjustment between wastewater types. Different wastewaters may require different membranes, cleaning regimes, chemical dosages, and control logic. This point reinforces the broader lesson that a textile recycling solution should not be copied from one segment to another without a feed-quality basis and a staged commissioning plan. However, these limitations are only for the pilot and not for the full scale project.



Integrated pilot flow schematic diagram

5 Pilot performance: reactive dyeing wastewater

The woven reactive dyeing (from a woven dyeing and finishing factory) case is the most technically important part of the pilot because it exposes the limits of a straightforward UF-RO-reject-treatment configuration under high-TDS, high-color conditions. The project used this case to show both the strength of the membrane system - very high-quality permeate - and the weakness of the initial reject-treatment design - insufficient removal of refractory color with electrocoagulation alone.

In the conducted trial, the pilot received about 5 m^3/h of ETP-treated reactive dyeing wastewater. The incoming quality signal was approximately neutral pH, COD below 150 mg/L, BOD_5 below 30 mg/L, color around 1,200 Pt-Co, TDS below 3,000 mg/L, and TSS below 30 mg/L. These values are notable because they show that conventional biological treatment has already reduced bulk load substantially. Yet despite this, the water still contained enough dissolved salt and residual color to make the membrane-and-reject-management problem non-trivial.

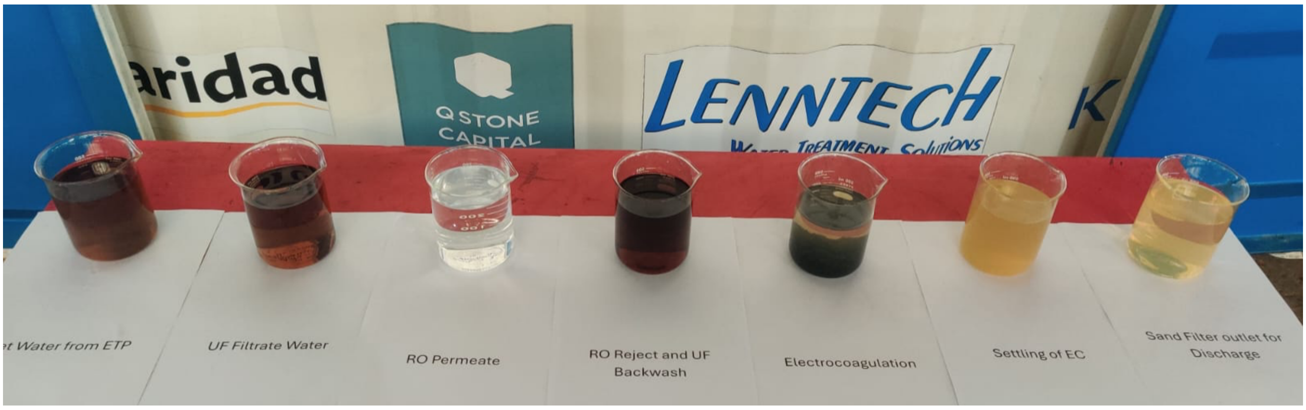
Treatment stage	Indicative flow / disposition	Key values of the water in different stages	Interpretation
ETP-treated influent	5 m^3/h to pilot	COD <150 mg/L, BOD <30 mg/L, color about 1,200 Pt-Co, TDS <3,000 mg/L, TSS <30 mg/L.	Feed is already biologically treated, but still difficult for recycle because of dissolved salts and color remain.
UF filtrate	About 95% of feed continues; about 5% reserved for backwash	COD about 120 mg/L, color about 1,200 Pt-Co, TDS about 3,000 mg/L, TSS reduced to about 5 mg/L.	UF primarily protects RO by removing solids; it does not materially reduce dissolved load or color.
RO permeate	About 3.0 m^3/h, or about 60% of total feed, available for recycle	COD about 5 mg/L, BOD about 2 mg/L, color 0, TDS about 100 mg/L, TSS 0.	RO performed strongly in producing recycled water of very high clarity and low salinity.

Treatment stage	Indicative flow / disposition	Key values of the water in different stages	Interpretation
RO reject and UF backwash combined	About 2.0 m^3/h to reject treatment	Combined feed to reject train around COD 488 mg/L, BOD 94 mg/L, color about 4,100 Pt-Co, TDS about 7,200 mg/L, TSS about 233 mg/L.	Pollutants are concentrated into a smaller, much harder-to-treat stream.
After EC, DAF, and sand filtration	Discharge stream after reject treatment	COD reduced to below 150 mg/L and TSS below 15 mg/L, but color remained around or below 200 Pt-Co.	Base reject treatment was insufficient to fully remove refractory color in reactive dyeing.
After polishing oxidation	Additional finishing step on reject-treatment effluent	COD reduced to below 80 mg/L and often below 50 mg/L; color reduced to below 150 Pt-Co and often around 100.	Polishing oxidation solved the residual color problem but added cost and process complexity.

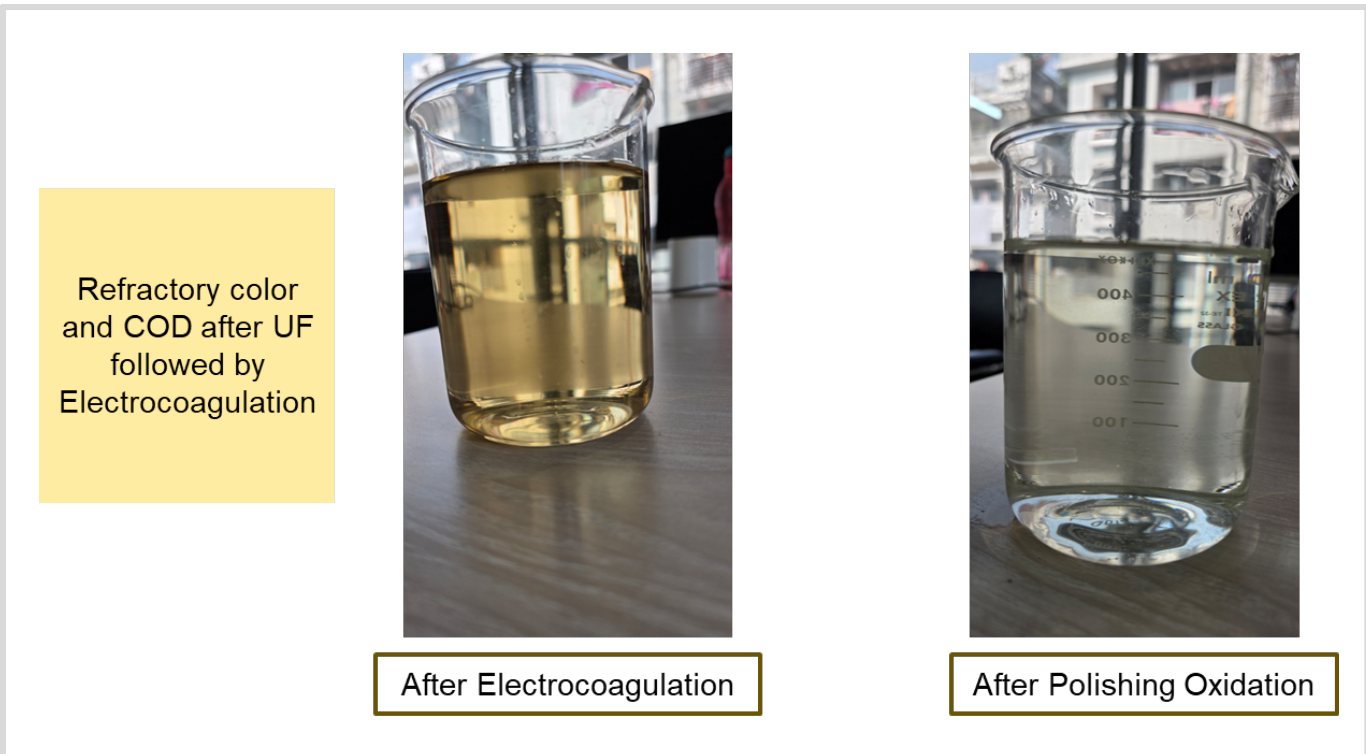
The above progression shows why the project team emphasized that recycling itself is not the hardest task. By the time the water reached the permeate tank, the process had done exactly what a recycling system is expected to do: it produced a clear, low-TDS stream suitable for recycling. The engineering problem moved downstream into the reject loop. RO reject from reactive dyeing was dark, saline, and chemically concentrated. When this stream was combined with UF backwash, the reject-treatment train had to deal with both dissolved load and destabilized suspended matter.

Electrocoagulation followed by DAF and sand filtration produced a large visible improvement, but not enough. One of the most useful realization of this pilot at reactive dyeing facility that the residual orange-yellow color after electrocoagulation was not simply iron carryover from sacrificial electrodes. Iron in the treated water was near zero - around 0.1 to 0.2 mg/L - and that the persistent color should instead be read as refractory color, meaning color associated with compounds not readily removed by the electrocoagulation only.

This finding is a major design lesson. For reactive dyeing wastewater, a recycle plant that relies on UF, RO, electrocoagulation, DAF, and sand filtration alone may still underperform against ZDHC progressive limit for color and COD objectives. The project therefore concluded that polishing oxidation is not optional in this segment when a tighter discharge or ZDHC progressive limit target is pursued.



Visual progression of reactive dyeing water through major pilot stages



Reactive dyeing reject-treatment results before and after polishing oxidation

5.1 Polishing oxidation options and cost implication

The project identified several candidate oxidation routes for this polishing duty: hydrogen peroxide / Fenton-type treatment, ozonation, combined ozone and hydrogen peroxide, UV-assisted oxidation, and electro-oxidation / electro-Fenton variants. The report does not rank these options because the source materials did not provide comparative pilot data by oxidation chemistry. What matters for this report is the operational conclusion: a post-EC color-removal step is required for reactive dyeing if the project aims to consistently reduce refractory color and residual COD.

That technical fix has an economic consequence. The project indicated an incremental cost of roughly BDT 5-7 per m3 for polishing oxidation alone. This cost is modest relative to full thermal ZLD, but it is not negligible; it should therefore be explicitly budgeted whenever the feed segment resembles the reactive dyeing case rather than the denim washing case.

Operational lesson from the reactive-dyeing case

- Permeate quality was not the limiting factor; the challenge was the concentrated reject.
- Electrocoagulation improves the reject substantially, but refractory color remained problematic.
- Polishing oxidation can close the compliance gap, but it adds cost and complexity.
- Reported recovery in this segment was generally about 60-65 percent, with around 70 percent achievable under favorable conditions.
- The recycling percentage can be increased to 75% with first stage RO for full scale project.

Treated Wastewater from Pilot Plant (Reactive Dyeing)

Third Party Test Result for Water Characteristics from Different Stages: Woven Fabric Reactive Dyeing case

Parameter	Unit	ETP treated effluent	UF filtrate (RO feed)	UF backwash / AOP feed	RO permeate	RO reject	Total AOP feed	Discharge after sand filtration	Polishing oxidation target	ZDHC Progressive Limit
Recycling	%	--	95	5	60	35	40	40	40	N/A
Flow	m^3/hr	5	5	0.25	3	1.75	2	2	2	N/A
pH	-	7	7	7	7	7	7	7.00	7.00	6 – 9
COD	mg/L	<150	120	720	5	442	488	<150	<80	<80
BOD_5	mg/L	<30	25	125	2	89	94	<30	<15	<15
Color	Pt-Co	<1200	1200	2150	0	4370	4100	<200	<150	<100
TDS	mg/L	<3000	3000	3000	100	7200	7200	>7200	>7200	>7200
TSS	mg/L	<30	5	1300	0	19	233	<15	<15	<15

6 Pilot performance: denim washing wastewater

The denim washing case serves as the counterpoint to reactive dyeing. It demonstrates that a lower-TDS, lower-color wastewater can unlock much higher recovery and much simpler reject management, even with the same overall pilot architecture. The pilot had moved to a denim washing factory after the reactive dyeing trials, allowing a direct comparison between the two segments under a common treatment philosophy.

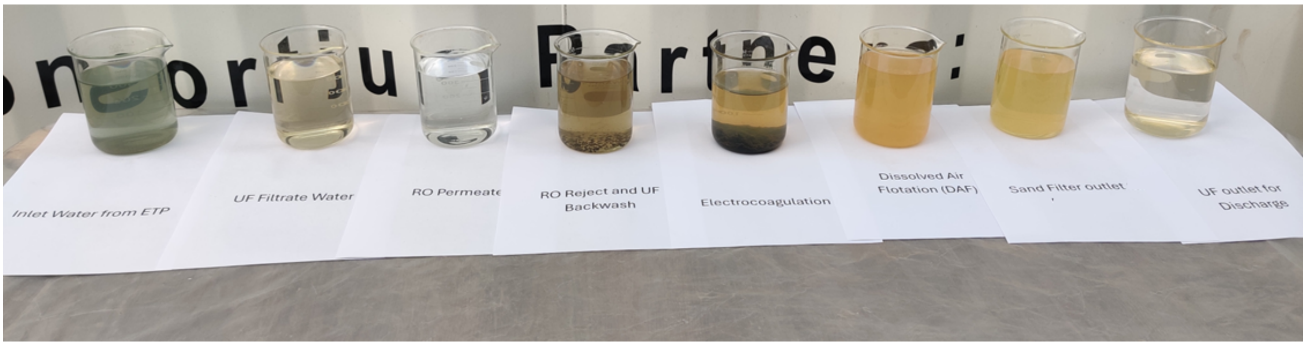
The most striking observation in the denim case is that ultrafiltration itself produced a visible improvement in water quality. The project identified this by noting that a substantial portion of denim washing pollutants is colloidal. In practical terms, that means the front-end membrane step removes more of the objectionable load before the water even reaches RO. This changes both the burden on the RO system and the character of the reject stream that must be treated afterward.

Treatment stage	Indicative flow / disposition	Key values of the water from different stages	Interpretation
ETP-treated influent	5 m^3/h to pilot	COD below 100 mg/L, BOD below 30 mg/L, color around 120 Pt-Co, TDS below 1,000 mg/L, TSS below 30 mg/L.	Feed is materially easier than reactive dyeing because dissolved salts and color are much lower.
UF filtrate	About 95% of feed continues; about 5% to backwash	COD around 65 mg/L, BOD around 13 mg/L, color around 115 Pt-Co, TDS about 1,000 mg/L, TSS about 5 mg/L.	UF gives a more meaningful visible polish because much of the pollution is colloidal.
RO permeate	About 4.0 m3/h, or around 80% of total feed, available for recycle	COD about 5 mg/L, BOD about 2 mg/L, color 0, TDS about 100 mg/L, TSS 0.	RO again produced excellent recycle water, but at higher recovery than in the reactive case.

Treatment stage	Indicative flow / disposition	Key values of the water from different stages	Interpretation
RO reject and UF backwash combined	About 1.0 m3/h to reject treatment	Combined feed to reject train around COD 222 mg/L, BOD 45 mg/L, color about 400 Pt-Co, TDS about 3,100 mg/L, TSS about 99 mg/L.	Reject is milder than in reactive dyeing, making downstream treatment simpler and cheaper.
After EC, DAF, and sand filtration	Discharge stream after reject treatment	COD below 80 mg/L, BOD below 15 mg/L, color below about 120 Pt-Co, TDS about 3,100 mg/L, TSS below 15 mg/L.	The base reject-treatment train was sufficient in the; no polishing oxidation was required.

The denim trial demonstrates a practical point with major economic consequences: the easier wastewater does not merely improve recovery, it also collapses the complexity of the reject train. Because the reject volume is lower and its chemistry is less severe, the treatment steps after RO become simpler, and the system avoids the incremental polishing oxidation cost that was necessary in reactive dyeing.

This difference is visible in both the water-quality table and the photo sequence. The reject from denim washing was still clearly more polluted, but it was not in the same class of difficulty as the reactive dyeing reject. As a result, the denim case stands out as the most immediately bankable pathway for scaling recycle systems, particularly for facilities under pressure to reduce freshwater intake without immediately moving to full ZLD.



Visual progression of denim washing water through major pilot stages

Third Party Test Result for Water Characteristics from Different Stages: Denim Washing case

Parameters	Measuring Unit	ETP WW before	ETP WW after	UF filtrate	RO stage 1 permeates	RO Stage 1 reject	RO stage 2 permeates	RO stage 2 Reject	UF backwash and RO	Sand filter feed tank	Sand filter 2 outlet	UF Filtrate after sand
Sample ID	--	ETPout	ETPcar	UF1	ROP1	ROR1	ROP2	ROR2	RORUFB	DAF	SF	UF2
COD	mg/L	24	-	ND	-	-	-	52	34	-	36	20
Conductivity	µS/cm	1144	1134	1132	289	1430	71	3618	2052	2089	2053	1830
p^H	--	7.5	7.6	7.5	7.7	7.3	7.8	7.7	7.9	8	7.8	7.4
TDS	mg/L	576	567	569	140	725	34	1899	1055	1071	1051	933
TSS	mg/L	26	ND	8	ND	7	ND	15	24	31	25	10
Iron	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hardness	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Color	Pt.Co.	24	26	24	ND	35	ND	134	155	167	119	17
Color (436nm; 525; 620nm)	m^{-1}	0.6; 0.1; 0.1	0.7; 0.1; 0.1	0.6; 0.1; 0.1	0.1; 0.1; 0.1	1.0; 0.1; 0.1	0.1; 0.1; 0.1	4.8; 1.7; 0.1	6.0; 3.3; 1.8	6.7; 2.9; 1.2	4.8; 2.1; 0.9	0.3; 0.1; 0.1
Silica		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

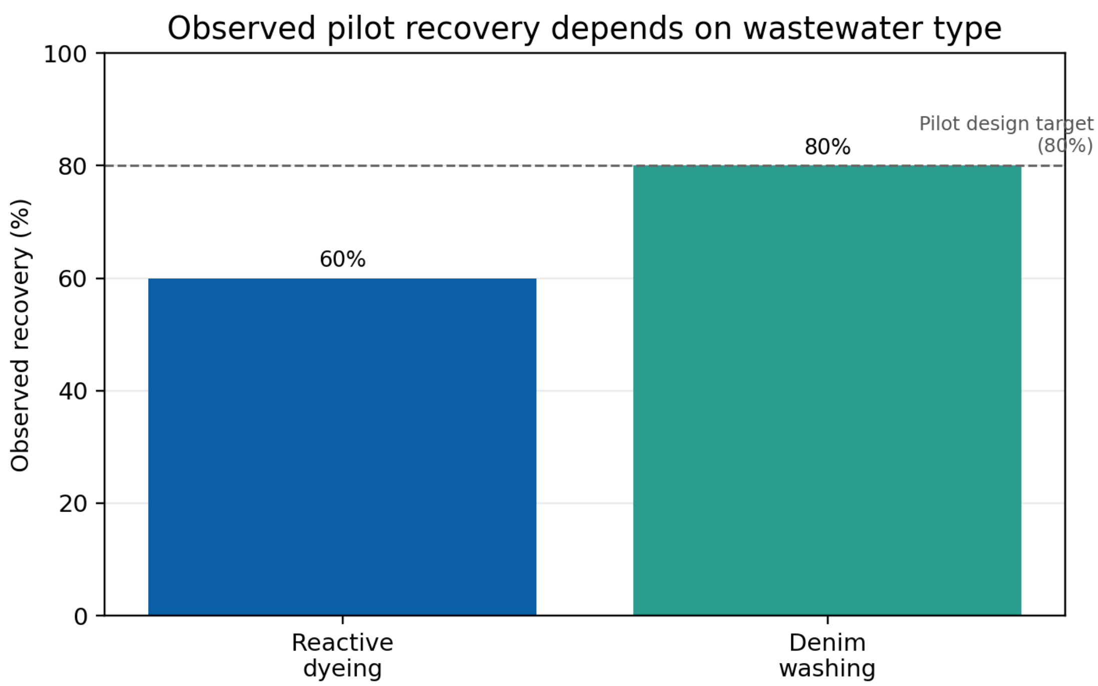
7 Cross-segment comparison and treatment selection logic

Comparing the two pilot cases reveals a simple but powerful treatment-selection logic. The closer the ETP-treated feed is to the denim profile - lower TDS, lower color, and stronger colloidal contribution - the more attractive high-recovery recycling becomes. The closer the feed is to the reactive dyeing profile - high salt, strong residual color, and difficult reject chemistry - the more likely the project will need extra polishing, careful recovery control, and a stronger business case to justify the added operating burden.

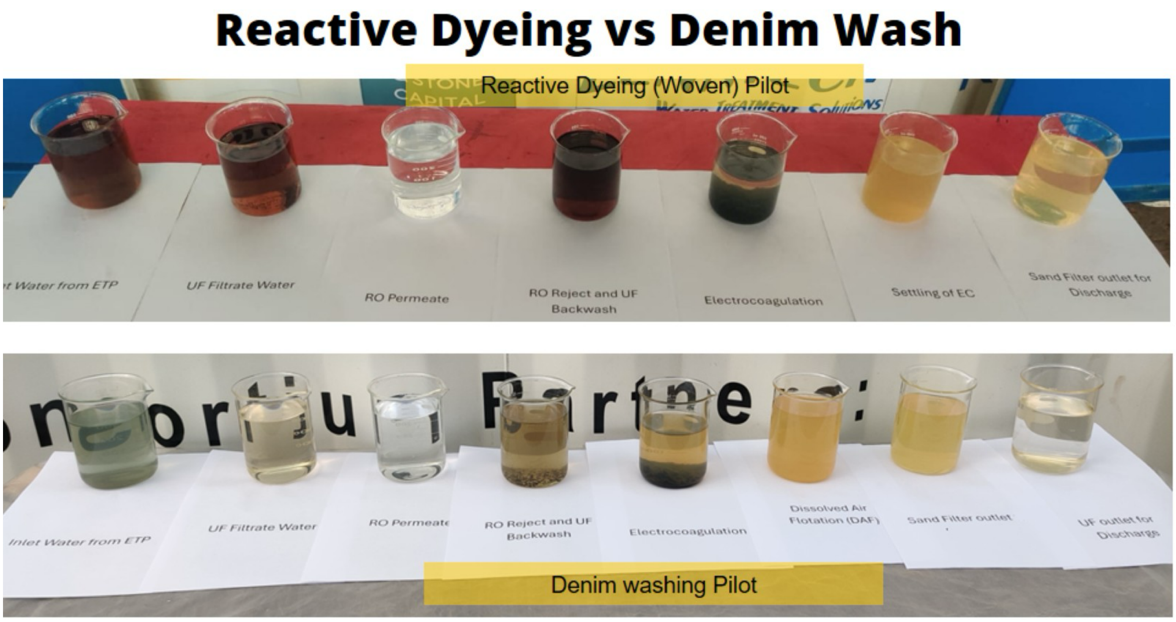
This comparison also explains why blanket statements such as "membrane recycling is financially viable for textiles" are incomplete. Membrane recycling may be financially viable for a denim-washing-type feed at recoveries around 80% or higher, while the same statement may become much harder to defend for reactive dyeing unless the project has clear value for water reuse, discharge reduction, brand compliance, or future ZLD readiness.

Criterion	Reactive dyeing	Denim washing	Why the difference matters	Design consequence
Feed TDS	High; around 2,500-3,000 mg/L in the example.	Low; around or below 1,000 mg/L in the example.	Higher TDS raises RO pressure and limits practical recovery.	Reactive systems need tighter recovery control and stronger scaling management.
Residual color	Very high and chemically resistant.	Much lower and easier to handle.	Residual color governs whether reject treatment can stop at EC/DAF or needs oxidation polishing.	Reactive systems should budget for polishing oxidation; denim may not need it.
Reject severity	Dark, highly concentrated, TDS around 7,200 mg/L in combined reject feed.	Milder, around 3,100 mg/L in combined reject feed.	Reject severity drives the cost of every subsequent step.	Brine management strategy becomes a first-order design question in reactive dyeing.

Criterion	Reactive dyeing	Denim washing	Why the difference matters	Design consequence
Observed recovery	About 60-70% depending on feed conditions.	About 80% or slightly more.	Recovery is the main determinant of water savings and reject volume.	Denim offers faster bankability for recycle projects. Reactive dyeing also can reach up to 75% recycling with appropriate design.
Need for polishing oxidation	Yes, to meet the progressive limit of ZDHC standard for color and COD performance.	No, not needed.	Additional polishing affects both OPEX and process simplicity.	Project developers should segment pipelines rather than standardize one universal train.



Observed pilot recovery differs significantly by wastewater type



Visual comparison: reactive dyeing versus denim washing

8 Economic assessment: 70% recycle systems and conventional ZLD

The project considered 100 m^3/h plant delivering 70% recycling with 30% discharge at a ZDHC progressive limit. The second is conventional ZLD for the same scale, extending the membrane train and then relying on thermal evaporation and drying to eliminate liquid discharge. The difference between the two is dramatic and is central to understanding why brine management is the strategic issue for future development.

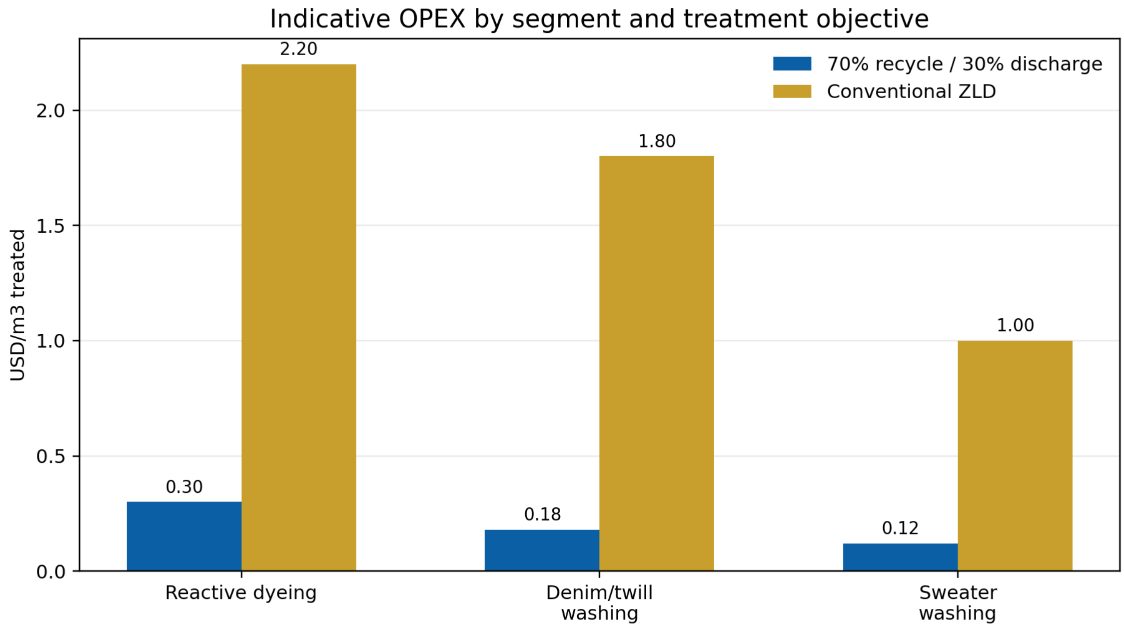
It is important to distinguish these full-scale indicative values from pilot OPEX. It is explicitly noted that pilot OPEX is not representative of scaled OPEX. Pilot operation is intentionally more expensive because it is optimized for learning, adjustment, and proof of concept rather than for commercial efficiency. The indicative values below therefore refer to scale-up estimates, not to the short pilot campaigns themselves.

Segment	Treatment objective	Indicative CAPEX	Indicative OPEX
Reactive dyeing	70% recycle and 30% discharge as per ZDHC progressive limit	USD 2.0 million	USD 0.30 per m^3 (roughly BDT 45-50/m^3)
Denim/twill washing	70% recycle and 30% discharge as per ZDHC progressive limit	USD 1.2 million	USD 0.18 per m^3 (roughly BDT 18-20/ m^3)
Sweater washing	70% recycle and 30% discharge as per ZDHC progressive limit	USD 0.9 million	USD 0.12 per m^3 (roughly BDT 13-15/ m^3)
Reactive dyeing	Conventional ZLD	USD 3.5 million	USD 2.20 per m^3
Denim/twill washing	Conventional ZLD	USD 2.0 million	USD 1.80 per m^3
Sweater washing	Conventional ZLD	USD 1.2 million	USD 1.00 per m^3

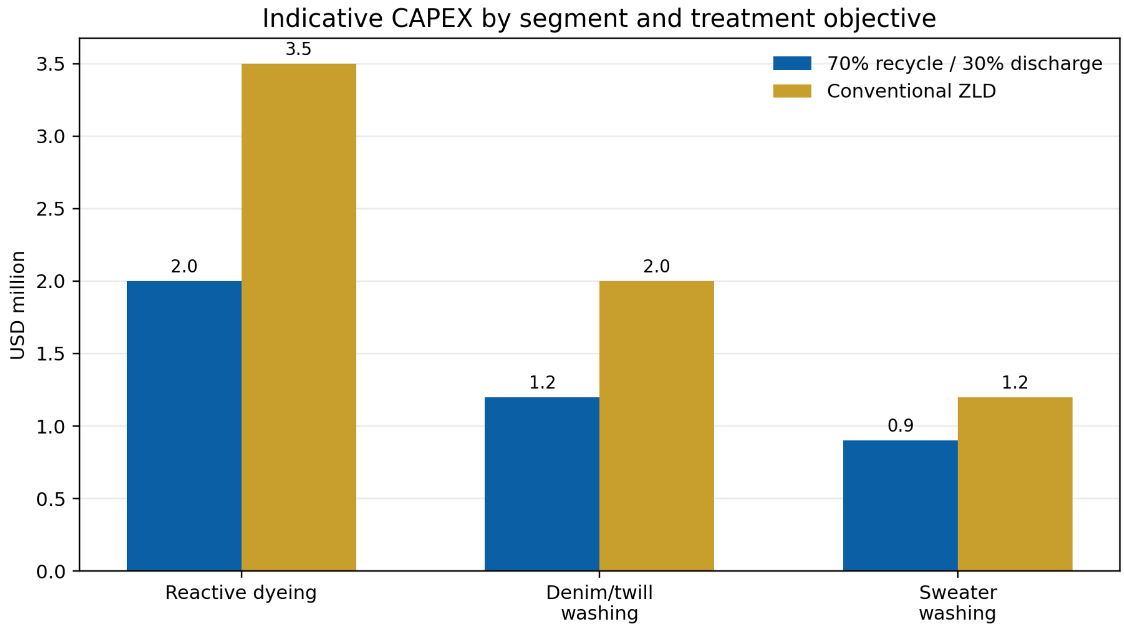
The comparison shows that the move from partial recycle to conventional ZLD multiplies OPEX by a factor that far exceeds the incremental water recovered. The project identified that the thermal tail - multiple-effect evaporation followed by agitated thin-film drying - can cost as much as the entire upstream UF-to-RO block. In other words, once a project enters the thermal zone, the economics are no longer dominated by permeate generation but by what it costs to drive the last concentrate to dryness.

For reactive dyeing, roughly half of the partial-recycle OPEX of USD 0.30/m3 was already attributable to reject management rather than to the generation of recycle water itself. This observation is crucial because it means future innovation should target the back end of the process. Every incremental improvement in reject concentration, purification, or salt recovery has a disproportionate effect on overall economics.

A further estimate of the cost of evaporating for one cubic meter of wastewater in an MEE/ATFD route at around BDT 1,500. Even if that value is treated as a high-level discussion estimate rather than a procurement-grade number, it underlines the same conclusion: full ZLD becomes economically punishing when the process crosses into thermal finishing.



Indicative OPEX by segment and treatment objective



Indicative CAPEX by segment and treatment objective

Cost disclaimer retained from the source materials

All presented cost figures are indicative and can vary with supplier, membrane selection, local tax treatment, energy tariff, chemical consumption, consumables, and the actual design basis of the host factory. They should therefore be used for screening and discussion, not as final budget numbers.

9 Energy, operability, and membrane integrity considerations

The pilot identified several practical engineering points. First, energy demand is strongly tied to feed salinity. The electricity consumption in the higher-TDS reactive dyeing case was roughly 35-40% higher than in the denim case because higher TDS requires higher RO operating pressure. This relationship is basic membrane physics, but its practical implication is often underestimated: a factory that wants higher recycle must be prepared not only for a larger membrane train, but also for a higher energy-intensity regime if feed salinity is not reduced upstream.

Second, the project identified the importance of feed conditioning and membrane protection. An SDI value of less than 3 after ultrafiltration is recommended for the reactive dyeing case during start-up testing. That value matters because it indicates the RO feed was sufficiently conditioned from a particulate fouling standpoint, even though dissolved load and color remained challenging. The project therefore reinforces a useful distinction: low SDI alone does not guarantee easy recovery if osmotic pressure and dissolved contaminants remain high.

Third, it is identified that all silica behaves the same way. Colloidal silica, often associated with groundwater, can be removed by UF. Soluble silica - discussed in relation to silicone softeners - is more problematic in later-stage concentration. Silica is not a major factor for a properly designed first-stage single-stage RO system when correct antiscalant selection and dosing are used, but it becomes important beyond the second stage as concentration rises. This point is especially relevant when moving from partial recycle toward higher-stage concentration or ZLD.

Operational issue	Project observation	Engineering implication
Energy demand	Reactive dyeing consumed roughly 35-40% more electricity than denim washing because of higher TDS and pressure demand.	Energy estimates must be segment-specific; pressure optimization and low-pressure membranes matter.
Motor and membrane selection	IE4/IE5 motors and comparatively low-pressure RO membranes were	Efficiency should be pursued at the design stage, but always against a

Operational issue	Project observation	Engineering implication
	mentioned as optimization measures.	performance "sweet spot" rather than through pure minimization.
SDI after UF	Less than 3 was cited during initial start-up testing for the reactive case.	UF can condition the feed effectively for RO even when dissolved challenges remain.
Silica	Not a major issue in first-stage RO if designed properly; more relevant in later concentration stages.	Higher-stage brine concentration requires more explicit scaling management.
Local know-how	Continuous service and troubleshooting remain a constraint.	Scale-up should include training, SOPs, and local service arrangements - not equipment alone.

The project also made a broader process-management point: recycling should not be treated as a substitute for water efficiency at source. Production teams often defend nominal water-use values that are lower than actual realized consumption. That observation is qualitative rather than audited in this report, but it is strategically important. Recycling becomes more affordable when upstream water use is first controlled, because every avoided cubic meter of use also avoids a cubic meter of water that would later need to be recycled, concentrated, or evaporated.

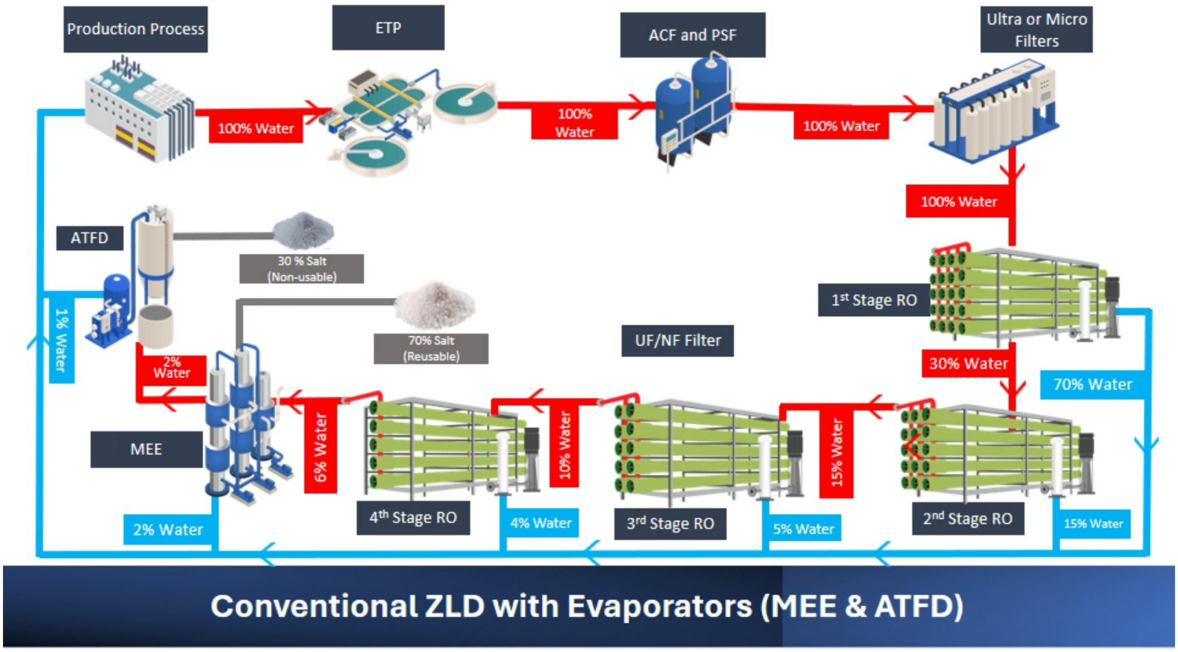
Taken together, these operational points suggest that successful scale-up depends on both process design and organizational readiness. A plant may buy the right membranes and still underperform if it lacks feed monitoring, dosing discipline, cleaning management, or local technical support. In that sense, the pilot was not only a technology demonstration; it was also an implicit warning against underestimating operational maturity.

10 Brine management, ZLD pathway, and next pilot phase

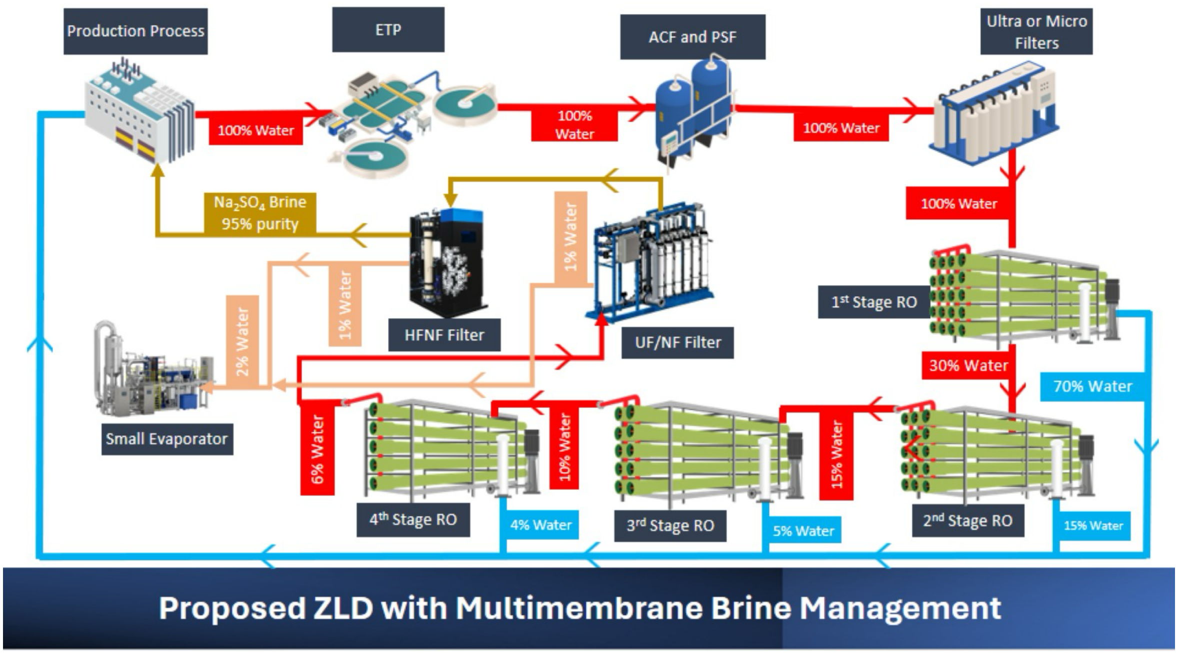
By the end of the project, the strategic question had clearly shifted from "can we make recycle water?" to "what do we do with the remaining concentrate?". This is the correct framing. In both pilot cases, the permeate stream was technically convincing. The unresolved issue was what to do with the increasingly saline and chemically difficult reject stream if the project wants to move beyond partial recycle and toward ZLD or near-ZLD performance.

The report presented a conventional ZLD route based on successive RO stages followed by multiple-effect evaporation and ATFD. In the schematic, Stage-1 RO recovered about 70% water, Stage-2 recovered an additional 15%, Stage-3 about 5%, and a further high-pressure step about 4%, leaving a very high-TDS residual concentrate to thermal evaporation. The remaining thermal train then yielded a small additional condensate stream and salt fractions, some reusable and some not. The message was not that the route is impossible - on the contrary, it is technically proven - but that it is expensive and dominated by the final thermal steps.

The proposed next phase is therefore a multimembrane salt-separation concept intended to shrink the thermal tail. The project identified a route in which the concentrated reject would be further processed using hollow-fiber and nanofiltration-type steps to produce a sodium sulfate brine of around 95% purity. That number was explicitly presented as a theoretical expectation, not a demonstrated pilot result. The aspiration is that only around 1-2% of the original water would then need to pass to a small evaporator, dramatically reducing both OPEX and CAPEX compared with conventional ZLD.



Conventional ZLD route



Proposed multimembrane brine purification and reduced-evaporation pathway

Phase	Priority action	Expected technical question	Success signal
Near term	Complete detailed brine characterization by segment and confirm stability of the 70% recycle configuration.	How much of reject cost is driven by salt type, color chemistry, and flow variability?	Repeatable operation with stable recovery and repeatable reject chemistry.
Pilot phase 2	Run the proposed multimembrane brine-purification pilot.	Can sodium sulfate-rich brine be separated at useful purity without excessive membrane fouling or loss?	Demonstrated salt recovery, sharply reduced thermal load, and credible economics.
Scale-up preparation	Translate pilot findings into modular design packages for segment-specific plants.	What minimum design package is sufficient for bankability and procurement?	Segment-specific standard designs with local O&M capability and realistic guarantees.
Policy / ecosystem	Address import duties, service localization, and incentive structures.	How can adoption barriers be reduced beyond pure equipment optimization?	Improved investor confidence and a stronger local service market.

11 Recommendations and implementation roadmap

The pilot results support a pragmatic implementation strategy. First, factories should not move directly from generic interest in recycling to a universal full-ZLD procurement. Instead, they should segment facilities by wastewater type, quantify actual post-ETP water quality, and then choose between a higher-recovery partial-recycle route and a longer-term ZLD pathway. Denim and other lower-TDS washing segments are the strongest candidates for near-term scale-up.

Second, every design should explicitly separate the front-end recycle objective from the back-end reject objective. The pilot showed that these are not the same problem. A plant can have excellent permeate quality and still struggle with reject discharge, color, and salt concentration. Contracts, budgets, and performance guarantees should therefore state recovery, recycle-water quality, reject characteristics, and polishing or ZLD assumptions separately.

Third, local capability building should be treated as part of the project scope. Training, standard operating procedures, membrane cleaning protocols, feed monitoring routines, and local service arrangements are not optional extras. They are integral to system performance.

Stakeholder	Recommended action	Reason
Factories	Prioritize water audits, segment-based piloting, and feed-quality monitoring before large procurements.	Upstream control reduces both recycle cost and reject burden.
Technology providers	Offer performance envelopes by wastewater type rather than single headline recovery numbers.	Credibility improves when claims are tied to feed chemistry and reject strategy.
Program sponsors	Support second-phase brine management pilots and service localization.	The remaining innovation gap sits in reject management and ecosystem capability.
Policy makers	Review fiscal treatment of recycling equipment and consider targeted incentives for validated recycle systems.	High import cost and weak incentives slow adoption even where the technical case is strong.

What the proposed multimembrane concept is trying to achieve

- Concentrate brine further with high-pressure RO rather than evaporating large residual volumes too early.
- Purify a sodium-sulfate-rich stream that may be reusable in dyeing.
- Reduce the fraction of flow that ultimately requires evaporation to around 1-2 percent, as theorized in the presentation.
- Shift ZLD economics away from thermal evaporation and toward more selective membrane separation.

12 Implementation considerations for scale-up

The pilot findings point to a scale-up agenda that is as much institutional as technical. First, segment screening should become standard practice. Recycling projects should not be marketed as generic textile solutions; they should be matched to wastewater classes with different expected recovery and reject-treatment burdens. Second, project preparation should begin with source reduction. The presentation highlighted that production teams may understate actual water use, which means water audits and operating-discipline improvements can materially improve the economics of downstream recycling.

Third, local technical capacity is critical. The presenter repeatedly cited the lack of local advisory support and after-sales service as one of the main reasons factories remain cautious. For financiers and development partners, this suggests that hardware financing alone will not be sufficient. Successful scale-up will likely require bundled technical assistance, local O&M training, spare-parts planning, and stronger performance-verification norms. Fourth, future pilots should expand their monitoring envelope to include broader compliance parameters, energy performance, and brine chemistry—especially if the next generation of work focuses on high-pressure concentration and salt recovery.

Finally, policy settings matter. If imported membranes and related equipment continue to carry high duty burdens, first-mover adoption will remain expensive. The logic of the pilot therefore supports a package approach: segment-appropriate technology, localized capability, targeted incentives, and transparent performance reporting.

Practical scale-up sequence suggested by the pilot

- Step 1: strengthen production-side water accounting and reduce avoidable water use.
- Step 2: prioritize denim/twill and similarly lower-load streams for early commercial recycling projects.
- Step 3: design reactive-dyeing systems with realistic recovery expectations and a dedicated reject-finishing strategy.
- Step 4: pilot non-evaporative brine management before committing to large conventional ZLD investments.
- Step 5: embed local service capability and broaden analytical monitoring to include energy and brine chemistry.

13 Conclusion

The SMEP pilot demonstrates that textile wastewater recycling is technically feasible, but only if it is approached as a segment-specific process engineering problem rather than as a universal technology package. In both tested segments, the membrane train produced high-quality permeate suitable for recycle. The decisive difference between success cases and difficult cases lay in what happened after concentration: the chemistry, volume, and treatability of the reject stream determined recovery limits, polishing needs, and cost.

Reactive dyeing emerged as the difficult case because salt and refractory color remain significant even after conventional ETP treatment. In that segment, UF provided feed protection, RO produced excellent permeate, but electrocoagulation-based reject treatment alone was not sufficient. Polishing oxidation had to be added. Denim washing, by contrast, behaved as the easier near-term opportunity: lower TDS, milder color, easier reject treatment, and higher recovery.

Economically, the report confirms the strong logic for pursuing high-recovery recycle before conventional thermal ZLD wherever regulations and site conditions allow. The difference between partial recycle and full thermal ZLD is too large to ignore. The next phase should therefore focus on reject purification and salt recovery rather than simply adding more of the same membrane stages. If the proposed multimembrane brine-separation pathway can be validated, it may offer the missing bridge between technically credible recycling and financially scalable circular water systems for the textile sector.

End of the Report