SMEP PILOT PROJECT

Water Recycling Demonstration for the Textile Industry

Detailed Technical Report | February, 2026

PILOT STATUS	COUNTRY	SEGMENTS TESTED
COMPLETED	Bangladesh Textile Sector	2 Denim | Reactive Dye

80%+	60–70%	~100 mg/L	$0.30/m³	5 m³/h
Water Recovery - Denim	Water Recovery - Reactive Dye	Permeate TDS (both segments)	Cost vs $2.20 ZLD (Partial Recycle)	Pilot Throughput (3-container)

1. Project Purpose & Context

This report documents the findings of a pilot project funded by the United Kingdom's Foreign, Commonwealth and Development Office (FCDO) under the Sustainable Manufacturing and Environmental Pollution (SMEP) Programme[1], implemented in partnership with UNCTAD. The project was led by Solidaridad Network Asia Limited in consortium with QStone Capital, Lenntech, and Kingsley Engineering Services Corporation.

The SMEP pilot was positioned as a de-risking instrument for textile wastewater recycling in Bangladesh - a market facing simultaneous pressure from rising freshwater scarcity, buyer sustainability expectations, and ZDHC compliance requirements.

Bangladesh's textile sector is one of the most water-intensive manufacturing industries globally. With groundwater tables declining and discharge regulations tightening, the industry faces an urgent need for validated, cost-effective water recycling solutions. Yet adoption has been slow due to a combination of structural barriers that the SMEP pilot was explicitly designed to address.

[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

Key Structural Barriers Addressed

- Limited local technical expertise for membrane systems
- High import duties on recycling equipment reducing financial viability
- Weak after-sales and operations & maintenance (O&M) support ecosystem
- Absence of local performance benchmarks, undermining investor confidence
- No established framework for ZDHC progressive compliance at facility level

Design Objectives

The pilot was designed to:

1. Recover up to 80% of ETP-treated water as process-reuse quality permeate
2. Generate a defensible, data-backed understanding of reject-stream behaviour
3. Establish ZDHC progressive limit compliance thresholds by wastewater segment
4. Produce replicable system architecture and cost benchmarks for scale-up

2. System Architecture

The pilot system is a 3-module, containerised unit processing secondary ETP effluent. The modular design enables transport and rapid site deployment - a critical consideration in a sector where factory footprints and logistics vary considerably.

Module	Name	Function & Key Equipment
MODULE 1	**Front-End Conditioning & Ultrafiltration**	Bag filter → Cartridge filter → UF membrane. Removes TSS and reduces SDI to protect downstream RO elements. Does not remove TDS or color. Feed quality control is critical at this stage.
MODULE 2	**Two-Stage Reverse Osmosis**	Stage-1 RO → Stage-2 RO → Permeate tank. Produces recycle-quality water at ~100 mg/L TDS. Concentrates dissolved pollutants (TDS, color, COD) into a high-strength reject stream for downstream management.
MODULE 3	**Reject Management & Finishing**	EC (Electrocoagulation) → DAF (Dissolved Air Flotation) → Sand filter → Polishing oxidation (reactive dye segment only). Manages concentrated reject for discharge compliance or further processing. This module proved the most segment-specific in behaviour.

Critical Insight: The Reject Is the Real Challenge

Producing high-quality permeate is not the hardest engineering challenge in textile wastewater recycling. Managing the concentrated reject stream - its chemistry, volume, and treatability - is what determines recovery limits, polishing costs, and ultimately commercial viability. Every design decision in a textile recycling system should be evaluated through the lens of its reject consequence.

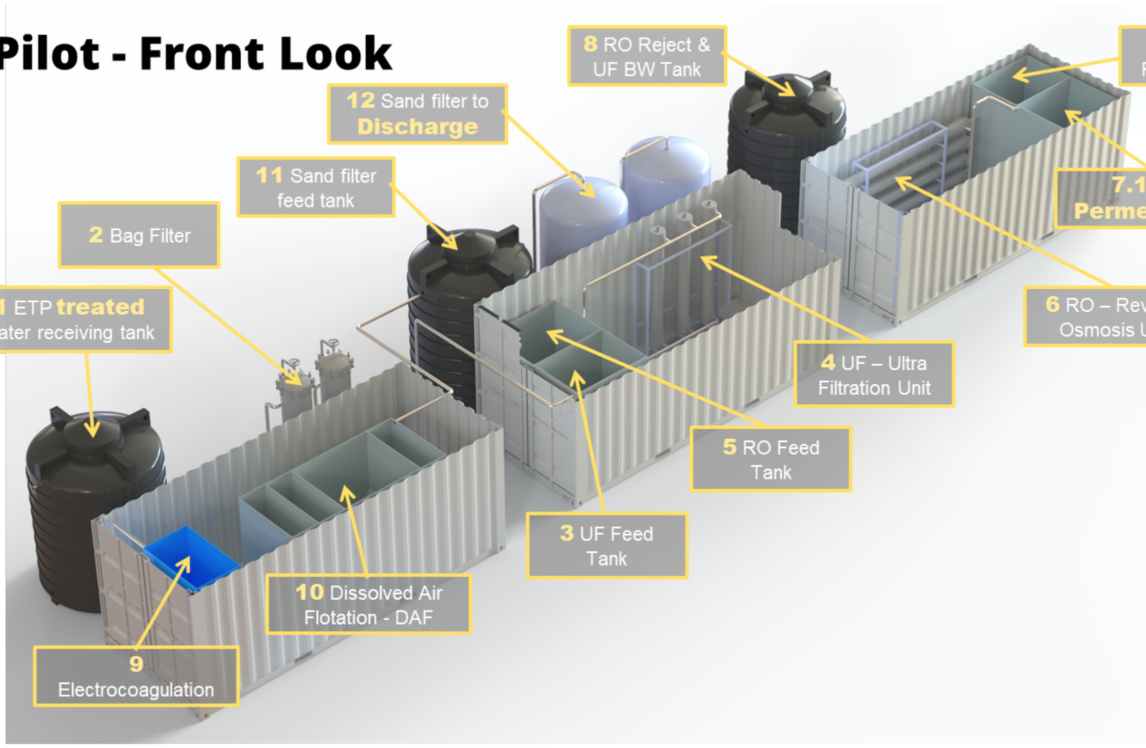

Figure 1. 3D render of the pilot system - front view showing all modules and principal equipment

Figure 2. The three pilot containers deployed on site in Bangladesh, sponsored by FCDO / SMEP and consortium partners

3. Pilot Performance: Segment-by-Segment Results

The pilot tested two distinct wastewater segments, each with different feed chemistry, recovery characteristics, and reject treatment requirements. Key findings confirm that no universal solution exists - system design must be anchored to segment-specific feed quality and reject strategy.

Parameter	Reactive Dyeing	Denim/Twill Washing	Key Takeaway
Water Recovery	~60–70%	80%+	Denim is the near-term priority segment for scale-up due to lower feed TDS and simpler reject.
Permeate TDS	~100 mg/L	~100 mg/L	RO permeate quality was excellent in both segments regardless of feed strength.
Feed TDS	High (>2,500 mg/L)	Lower (~1,000 mg/L)	TDS is the primary driver of recovery rate and reject treatment cost.
Reject Treatment	EC + DAF + polishing oxidation required	EC + DAF + sand filter sufficient	Refractory color in reactive dye reject demands an additional polishing oxidation step.
Main Bottleneck	High TDS + refractory color in reject	Front-end solids/colloid management	Different problems require segment-specific design - no universal solution exists.
Scale-up Readiness	Medium - requires validated reject polishing	High - simpler reject management pathway	Denim/twill should be prioritised for early commercial deployment.

4. Facility Comparative Analysis: Denim Washing Facility vs. Woven Reactive Dyeing Facility

In addition to segment-level analysis, the SMEP programme conducted a comparative technical assessment across two facilities - Denim Washing Facility and Woven Reactive Dyeing Facility - using detailed workbook data. This facility-level comparison reveals how real-world feed chemistry differences drive divergent system performance, energy demand, and reject quality outcomes.

4.1 Wastewater Feed Characteristics

The two facilities present materially different wastewater challenges. Woven Reactive Dyeing Facility operates with significantly stronger feed - average TDS of 2,237 mg/L versus 635 mg/L at Denim Washing Facility, and feed color of 1,144 Pt.Co versus 241 Pt.Co. This difference is not marginal; it fundamentally alters system sizing, energy consumption, and reject management requirements.

The implication is direct: a system sized and costed for Denim Washing Facility-type feed will be undersized and under-specified for Woven Reactive Dyeing Facility-type feed. Blanket technology offers with single headline performance numbers are therefore inappropriate for this sector.

4.2 Key Performance Indicators: Summary Comparison

Indicator	Denim Washing Facility	Woven Reactive Dyeing Facility	Comment
Feed TDS (mg/L)	635	2,237	Woven Reactive Dyeing Facility feed is ~3.5x stronger in dissolved solids
Feed Color (Pt.Co)	241	1,144	Woven Reactive Dyeing Facility feed is ~4.7x higher in color load
UF Stage Recovery (%)	75.6	66.5	Denim Washing Facility achieves stronger pretreatment recovery
RO Stage Recovery (%)	82.7	65.0	Denim Washing Facility delivers higher RO recovery due to lower feed TDS
Process Reuse Recovery (%)	80	67	Denim Washing Facility delivers better recycle-water yield
Total Liquid Recovery (%)	80	65	Difference driven by feed strength and system design
Total SEC - Pilot (kWh/m³ feed)	4.09	7.67	Woven Reactive Dyeing Facility is nearly 2x more energy intensive at pilot scale;

			full-scale SEC will be materially lower - see Section 4.4
Total SEC - Full-Scale Projection (kWh/m³)	**~1.08**	**~1.8 – 2.5**	Full-scale SEC is comparable across both facility types once pilot-scale inefficiencies are eliminated; dominated by AOP/EC+DAF at 44.2% share
Final COD - Sand Filter (mg/L)	**40**	**89**	Denim Washing Facility achieves lower and more stable residual COD
Final Color - After Sand Filters (Pt.Co)	**150**	**200**	Both facilities meet or approach ZDHC progressive limit after full treatment train

4.3 Stage-Wise Water Balance & Recovery

Stage-wise recovery profiles reveal where efficiency is gained or lost in each system. At the UF stage, Denim Washing Facility outperforms Woven Reactive Dyeing Facility (75.6% vs 66.5%), reflecting the benefit of lower feed turbidity and solids load. At the RO stage, Denim Washing Facility achieves 82.7% recovery versus 65.0% for Woven Reactive Dyeing Facility - a more material gap than initial headline figures suggested, driven directly by the higher osmotic pressure imposed by a 2,237 mg/L TDS feed.

Net process reuse recovery - the metric that matters most for water cost reduction - is 80% for the Denim Washing Facility type versus 67% for the Woven Reactive Dyeing Facility type. Total liquid recovery follows the same pattern at 80% versus 65% respectively, confirming that the denim washing segment offers a meaningfully stronger water recycling outcome at every stage of the process.

4.4 Energy Consumption: Pilot Scale vs. Full-Scale Projection

Energy intensity is a major differentiator between the two facility types. The woven reactive dyeing facility averages 7.67 kWh/m³ feed in total specific energy consumption (SEC), compared to 4.09 kWh/m³ at the denim washing facility at pilot scale. Critically, this gap does not originate in the front-end membrane block: UF energy is almost identical across both facilities (0.68 vs 0.67 kWh/m³), confirming that basic solids-conditioning duty is not the differentiator. The gap opens at RO and becomes decisive at the electrocoagulation stage.

Process Stage	Denim Washing Avg kWh/run	Reactive Dyeing Avg kWh/run	Difference vs Denim Washing	Denim Washing SEC (kWh/m³)	Reactive Dyeing SEC (kWh/m³)
Ultrafiltration (UF)	8.59	9.24	+7.7%	0.68	0.67
Reverse Osmosis (RO)	17.70	22.96	+29.7%	1.87	2.55
Electrocoagulation (EC)	25.04	73.31	+192.8%	5.49	11.91

Total	**51.33**	**105.51**	**+105.6%**	**4.09**	**7.67**

Note: SEC values above are from small-scale pilot operation (5 m³/h). Full-scale plant SEC will be materially lower - see table below.

Full-Scale Energy SEC Projection

The pilot SEC figures above are intentionally not representative of what a commercial-scale plant will consume. The summary table below presents full-scale specific energy estimates by process stage, showing the expected consumption profile at design-basis flow rates:

Stage	Specific Energy (kWh/m³)	Share of Total	Cost (Tk/day)
Ultrafiltration (UF)	0.245	22.7%	—
Reverse Osmosis (RO)	0.357	33.1%	—
Advanced Oxidation Process (EC and DAF)	1.432	44.2%	—
Selected Stages Total	**1.079***	**100.0%**	**—**

** Weighted average of selected stages. Cost column (Tk/day) to be completed with site-specific electricity tariff data.*

Why Pilot SEC Is Much Higher Than Full-Scale SEC

The gap between pilot SEC (4.09-7.67 kWh/m³) and full-scale projected SEC (~1.08 kWh/m³) is large and expected. It is not a sign of system inefficiency - it is a structural consequence of operating at 5 m³/h rather than the design-basis flow of a commercial plant. Five factors explain it:

1. Fixed auxiliary loads dominate at small scale. Control panels, instrumentation, lighting, dosing pumps, and compressed air systems draw near-constant power regardless of flow. At 5 m³/h, these overheads consume a disproportionately large share of total kWh per m³ of feed processed. At 100 m³/h, the same loads are spread over 20 times the volume.
2. Pump and motor efficiency is lower at pilot scale. High-efficiency IE4/IE5 motors and variable-frequency drives operate in their optimal efficiency band only at or near design flow. At pilot throughputs, centrifugal pumps operate far left of their best-efficiency point, consuming more energy per unit of flow.
3. EC electrode dosing is not optimised at pilot scale. Electrocoagulation current is often set conservatively during trials to ensure compliance, rather than being tuned to the minimum effective dose for a given feed chemistry. Full-scale EC design allows current density optimisation against measured feed load, typically reducing energy per m³ by 40-60% compared to pilot operation.
4. Start-up, cleaning, and standby periods inflate pilot kWh/run. Each pilot run includes membrane flushing, CIP cycles, warm-up periods, and inter-run standby time. Energy consumed during these non-productive periods is captured in the kWh/run figure but reduces to a negligible fraction at continuous full-scale operation.
5. Membrane area utilisation is sub-optimal. Pilot membrane elements operate at lower recovery per element than would be designed for a full-scale train, meaning more pressure energy is

applied per litre of permeate produced. Full-scale two-stage RO design is optimised for the feed TDS and target recovery, materially improving energy per m³ of recycle water generated.

The full-scale SEC projection of approximately 1.08 kWh/m³ should therefore be used for investment appraisals and operating cost modelling, not the pilot figures. The pilot SEC is a learning instrument - it reveals where energy is consumed and why, which is precisely the information needed to design an efficient full-scale system.

4.5 COD and Color Profiles Through the Full Treatment Train

The table below tracks COD, BOD_5, color, TDS, and TSS through every stage of the treatment process - from ETP-treated feed through to polishing oxidation - for both facilities. This end-to-end view reveals where quality is recovered, where it is concentrated, and where the critical compliance gaps remain.

Woven Reactive Dyeing Facility - Stage-wise Quality Profile

Treatment Stage	Flow (m³/h)	pH	COD (mg/L)	BOD_5 (mg/L)	Color (Pt.Co)	TDS (mg/L)	TSS (mg/L)	Recovery (%)
ETP-Treated Feed	5.0	7	<150	<30	<1,200	<3,000	<30	-
UF Filtrate (RO Feed)	5.0	7	120	25	1,200	3,000	5	95%
UF Backwash / AOP Feed	0.25	7	720	125	2,150	3,000	1,300	5%
RO Permeate	3.0	7	5	2	0	100	0	60%
RO Reject	1.75	7	442	89	4,370	7,200	19	35%
Combined EC/DAF Feed	2.0	7	488	94	4,100	7,200	233	40%
After Sand Filter	2.0	7	<150	<30	<200	>7,200	<15	40%
After Polishing Oxidation	2.0	7	<80	<15	<150	>7,200	<15	40%
ZDHC Progressive Limit	**-**	**6–9**	**<80**	**<15**	**<100**	**-**	**<15**	**-**

Denim Washing Facility - Stage-wise Quality Profile

Treatment Stage	Flow (m³/h)	pH	COD (mg/L)	BOD_5 (mg/L)	Color (Pt.Co)	TDS (mg/L)	TSS (mg/L)	Recovery (%)
ETP-Treated Feed	5.0	7	<100	<30	~120	<1,000	<30	-
UF Filtrate (RO Feed)	5.0	7	65	13	115	1,000	5	95%
UF Backwash	0.25	7	-	-	-	-	-	5%
RO Permeate	4.0	7	5	2	0	100	0	80%
RO Reject	1.0	7	-	-	-	-	-	-

Combined EC/DAF Feed	1.0	7	222	45	~400	3,100	99	-
After Sand Filter	1.0	7	<80	<15	<120	3,100	<15	-
Polishing Oxidation	Not required - EC + DAF + Sand Filter achieved ZDHC-compliant discharge without additional oxidation							
ZDHC Progressive Limit	**-**	**6–9**	**<80**	**<15**	**<100**	**-**	**<15**	**-**

The end-to-end profiles confirm three critical findings. First, RO permeate quality is excellent in both facilities - COD drops to 5 mg/L and color is eliminated entirely, regardless of how difficult the feed was. This confirms that permeate generation is not where systems fail.

Second, the treatment paths diverge sharply at the reject stage. For the Woven Reactive Dyeing Facility, EC and DAF alone leave color at ~200 Pt.Co after sand filtration - still above the ZDHC progressive limit of <100 Pt.Co. Polishing oxidation is required to bring color below 150 Pt.Co and COD below 80 mg/L. For the Denim Washing Facility, EC + DAF + sand filter alone achieves <80 mg/L COD and <120 Pt.Co color, meeting discharge targets without any polishing oxidation step - a significant operational and cost advantage.

Third, TDS remains elevated in the reject discharge stream of both facilities (>3,100–7,200 mg/L). This is expected given the partial-recycle design; dissolved salts concentrated by RO cannot be removed by EC or oxidation alone. Managing this TDS tail is the central motivation for the proposed multi-membrane brine purification pathway described in Section 6.

5. Economic Assessment

The economic case for partial recycle over conventional Zero Liquid Discharge (ZLD) is compelling. At pilot-derived costs, partial recycle at 70% recovery produces treated water at approximately $0.30/m³, compared to $2.20/m³ for conventional thermal ZLD - a 7x cost difference that creates an overwhelming logic for staged adoption.

System / Approach	Cost (100 m³/h plant)	Relative Cost
Partial Recycle - Membrane (70% recovery)	**~$0.30 / m³**	**Baseline**
Conventional ZLD (thermal - MEE + ATFD)	**~$2.20 / m³**	**~7x more expensive**

Cost Drivers & Energy Premium at Woven Reactive Dyeing Facility

Conventional ZLD cost is dominated by the multi-effect evaporator (MEE) and agitated thin-film dryer (ATFD), which carry high capital and operating costs and make thermal ZLD prohibitively expensive for most factories. The energy intensity comparison between Denim Washing Facility and Woven Reactive

Dyeing Facility (4.09 vs 7.67 kWh/m³) directly translates to operating cost differences: at industrial electricity tariffs, Woven Reactive Dyeing Facility's additional 3.58 kWh/m³ represents a significant ongoing cost premium that must be factored into investment appraisals for high-TDS facilities.

This reinforces the economic case for segment-specific design: a factory operator considering investment in recycling based on Denim Washing Facility-type performance data would face a material financial shock if their actual wastewater profile resembles Woven Reactive Dyeing Facility. Feed characterisation before system procurement is therefore not optional - it is a financial risk management imperative.

6. Brine Management & Next Phase Technology Pathway

The pilot conclusively identified reject and brine management as the central unresolved challenge in textile wastewater recycling. In both facilities and both segments, the membrane train produces high-quality permeate with consistency. What determines system viability - technically and economically - is what happens to the concentrated reject stream.

6.1 The Brine Problem: Why Thermal ZLD Is Not the Answer

Conventional ZLD routes the RO reject to thermal evaporation (MEE) followed by crystallisation (ATFD) to produce a dry salt cake. This approach is technically mature but economically prohibitive at the cost levels required for Bangladesh's export-oriented textile sector. The ~7x cost disadvantage of thermal ZLD over partial recycle is not a design refinement problem - it is a fundamental thermodynamic cost of evaporating large volumes of water against latent heat.

The next phase must therefore focus on reducing the fraction of the waste stream that requires thermal treatment - ideally to 1–2% of total flow - by extracting maximum value and volume from the concentrate using membrane-based routes before any thermal step.

6.2 Proposed Multi-Membrane Brine Purification Pathway

The proposed next-phase pathway centres on a multi-membrane brine purification route designed to avoid thermal evaporation except for a residual tail:

1. Further concentrate RO reject with high-pressure RO (HPRO) or Osmotically Assisted RO - deferring the thermal step while extracting additional clean water from the brine.
2. Separate and purify the sodium-sulfate stream using selective nanofiltration or electrodialysis - this stream may be reusable in dyeing processes, creating a circular economy loop.
3. Reduce the fraction requiring evaporation to ~1-2% of total system flow by maximising membrane concentration before any thermal step.
4. Shift ZLD economics from thermal-dominated to selective membrane separation - fundamentally redefining the cost structure of compliance-grade water management.

Strategic Significance

If validated, this multi-membrane route could offer the missing bridge between technically credible recycling and financially scalable circular water systems for the textile sector. It would allow factories to achieve effective ZLD-level compliance at partial recycle costs - transforming the economics of sustainable water management in Bangladesh and comparable manufacturing markets.

7. Recommendations & Implementation Roadmap

7.1 Stakeholder Recommendations

Stakeholder	Recommended Action	Reason	Scale-up Priority
Factories	Conduct water audits; segment-based piloting; monitor feed quality before large procurements.	Upstream control reduces both recycle cost and reject burden. Feed characterisation is a financial risk management imperative.	Prioritise denim/twill. Design reactive-dye systems with realistic recovery expectations and reject polishing provisions.
Technology Providers	Offer performance envelopes by wastewater type, not single headline recovery numbers.	Credibility improves when claims are tied to feed chemistry, energy cost, and reject strategy - not just permeate TDS.	Provide transparent, segment-specific performance guarantees that explicitly reference feed TDS bands.
Programme Sponsors	Support second-phase brine management pilots and service localisation programmes.	The remaining innovation gap sits in reject management and O&M ecosystem capability - not permeate production.	Bundle technical assistance, O&M training, and stronger performance-verification norms into future programme design.
Policy Makers	Review fiscal treatment of recycling equipment; consider targeted incentives for validated recycle systems.	High import duties and weak incentives slow adoption even where the technical and economic case is strong.	Improved investor confidence, stronger local service market, and accelerated compliance with discharge standards.

7.2 Practical Scale-Up Sequence

01	**Water Accounting**	Strengthen water accounting at factory level and reduce avoidable water use through process optimisation before committing to capital-intensive recycling investment.
02	**Denim/Twill Priority**	Prioritise denim/twill washing segments for early commercial recycling projects. Lower feed TDS, simpler reject chemistry, and 80%+ recovery rates make this the commercially strongest entry point.
03	**Reactive Dye Design**	Design reactive-dye segment systems with realistic recovery expectations (60–70%) and explicit reject treatment provisions including polishing oxidation capacity.
04	**Brine Piloting**	Pilot non-evaporative brine management approaches (HPRO, selective NF, electrodialysis) before committing to conventional thermal ZLD capital expenditure.

05	**Service Ecosystem**	Embed local service capability, O&M training, and performance verification norms. Broaden monitoring to include energy consumption and brine chemistry alongside water volume metrics.

8. Conclusion

The SMEP pilot confirms that partial water recycling in the textile sector is technically feasible, economically compelling, and ready for commercial scale-up - without waiting for full Zero Liquid Discharge. In both tested segments, the membrane train consistently produced recycle-quality permeate at around 100 mg/L TDS, suitable for direct return to production processes. Partial recycling at 70-80% recovery is not a compromise position; it is the most rational first step for factories that need to reduce freshwater consumption, lower operating costs, and meet compliance requirements today.

The facility-level comparison between the Denim Washing Facility and Woven Reactive Dyeing Facility confirms that partial recycling works across different wastewater types, with system design adjusted to segment-specific feed chemistry. Denim washing achieves 80%+ recovery with simpler reject management and a full-scale projected SEC of approximately 1.08 kWh/m³ - making it the strongest near-term commercial opportunity. Reactive dyeing achieves 60-70% recovery with an additional polishing oxidation step for reject treatment, but remains economically viable and discharge-compliant.

On discharge quality, both segments demonstrate the ability to meet the Bangladesh DoE color limit of 150 Pt.Co and the ZDHC Foundational Level - denim washing without polishing oxidation, reactive dyeing with it. This establishes a clear, validated compliance pathway for partial recycling that factories can act on now. At approximately \$0.30/m³ versus \$2.20/m³ for conventional thermal ZLD, the economic case is not marginal - it is decisive. Partial recycling delivers immediate water savings, immediate cost reduction, and immediate compliance progress, while the longer-term work on brine management and membrane-based salt recovery continues in parallel.

The central message of this pilot is therefore one of confidence: partial recycling works, it is affordable, and it is deployable. The next phase of innovation - non-evaporative brine purification - will make the economics even stronger. But factories do not need to wait for that next phase to act. The case for moving forward with partial recycling is established.

The bottom line

Partial water recycling in the textile sector is technically proven, economically compelling, and commercially ready. At \$0.30/m³ versus \$2.20/m³ for thermal ZLD, factories do not need to wait for full zero liquid discharge to act. The time to scale up is now.

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