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Developing a quality criteria framework for textile wastewater reuse and pilot-scale membrane treatment validation in Vietnam

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ABSTRACT

The textile industry consumes large quantities of water and generates significant volumes of wastewater, creating increasing pressure on water resources. This study investigated the current status of water use and reuse in 68 textile enterprises in Vietnam, developed a quality criteria framework for textile wastewater reuse, and evaluated the reuse potential of a pilot-scale membrane system (MF+UF, MF+UF+NF, and MF+UF+RO). The results showed that only 38.24% of the surveyed businesses currently reuse water, indicating considerable potential for expanding water recycling in the sector. A four-level water reuse quality criteria framework was proposed for different purpose applications. Pilot experiments demonstrated that the water output of MF+UF was suitable for reuse for less demanding processes such as cooling, equipment cleaning, air pollution control, and factory cleaning. The MF+UF+NF gave higher quality water, be reused for level 1, except for the EC parameter, and just reached levels 3 and 4. The RO permeate met the proposed water quality criteria for most high-quality reuse purposes. The findings provide a practical basis for promoting water reclamation and circular water management in the Vietnamese textile industry.

Keywords: textitle wastewater, nanofitration, reverse osmosis, membrane.

INTRODUCTION

Textile wastewater is among the most consuming water industrial processes worldwide, approximately 50 to over 200 L/kg of production. It generates large volumes of highly contaminated wastewater and 80–90% of the consumed water is ultimately discharged. It is characterized by color, organic matter, suspended solids, surfactants, salts, and various dye molecules [1, 2]. High water consumption, large wastewater generation, and high levels of pollution in textile industry have become major environmental and water resource management challenges, especially in the context of increasingly severe climate change, drought, and water depletion [3]. The Vietnamese textile and garment industry is one of the key industries, making a significant contribution to the national GDP and creating jobs for millions of workers. Therefore, water reuse is considered a potential and sustainable solution, helping to save resources, reduce operating costs and improve environmental protection efficiency. However, water reuse activities in the textile dyeing industry in Vietnam are currently limited, facing many obstacles in terms of investment costs, technology, and technical information. This highlights the urgent need for practical technical criteria that can support companies' choices of suitable technology for different water reuse purposes.

Conventional treatment technologies including coagulation, biological treatment, and oxidation, can effectively meet wastewater discharge requirements, but the treated effluents frequently fail to satisfy the stringent water quality requirements necessary for industrial water reuse, particularly in textile dyeing operations where water quality directly influences product quality and dyeing consistency. Advanced membrane technologies, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) have emerged as promising solutions. Therefore, integrating multiple membrane processes into a sequential treatment train has become an attractive strategy to improve overall treatment performance while minimizing membrane fouling and extending membrane lifespan [4-6].

Recently, pilot-scale and full-scale applications have demonstrated that integrated membrane systems such as UF–NF, UF–RO, and NF–RO can successfully recover high-quality water from textile wastewater while significantly reducing freshwater consumption. Results indicate that dye rejection exceeds 95%, COD removal reaches over 90%, and permeate quality satisfies process water requirements for textile production [5–7]. Gambelli et al. demonstrated the feasibility of UF-NF treatment for water reuse. However, the study mainly optimized NF operating conditions and did not establish reuse criteria for different industrial applications [8]. Atalay Eroğlu and Akbal (2025) studied an integrated treatment system combining Fenton oxidation and membrane filtration technology to improve water recovery from textile wastewater. The study focused on the simultaneous treatment of organic matter, color, and some dissolved ions to produce reusable water. The study emphasized oxidation-assisted membrane treatment for pollutant removal rather than evaluating water quality requirements for multiple reuse purposes [9].

Despite these advances, most previous studies have primarily focused on optimizing membrane operating conditions or maximizing pollutant removal efficiency, with treatment performance generally evaluated by comparing influent and final permeate quality compared with discharge or generic water reuse standards. Limited attention has been paid to the progressive evolution of water quality across individual membrane stages and whether intermediate treatment levels are already suitable for specific textile reuse applications. Furthermore, practical water reuse quality frameworks tailored to the operational requirements of the textile industry remain largely unavailable, particularly in developing countries such as Vietnam, where standardized reuse criteria have not yet been established for different water reuse purposes.

From that reality, the research "Developing a practical framework for textile wastewater reuse and pilot-scale membrane treatment validation in Vietnam" in Vietnam was aimed to: (1) Survey and assess the current state of production, water consumption, wastewater issues, and water reuse requirements from 68 businesses; (2) Develope a four-level water reuse quality criteria framework for different wastewater reuse purposes. (3) Evaluate a pilot advanced treatment model using multi-stage membrane technology, and assess water quality after each membrane stage compared with water reuse quality criteria. The findings provide practical guidance for selecting appropriate membrane configurations according to specific water reuse purposes while reducing investment and operating costs.

The novelty of this study lies in integrating a Vietnam-specific, four-level textile wastewater reuse quality framework with pilot-scale validation of three membrane treatment configurations (MF+UF, MF+UF+NF, and MF+UF+RO) using secondary effluents collected from three representative textile enterprises. Different membrane configurations were selected to represent progressively higher treatment levels and to determine the minimum treatment required for different water reuse applications (Figure 1).

MATERIALS AND METHODS

Surveying and collecting information from the textile businesses

This study surveyed 68 textile factories in Vietnam by survey form contained 31 questions to collect the information about the product, water consumption capacity, wastewater issues, water reuse state, water reuse quality requirement, and technologies applied in wastewater and water reuse treatment plants. The survey form was sent to textile companies in the southern, central, and

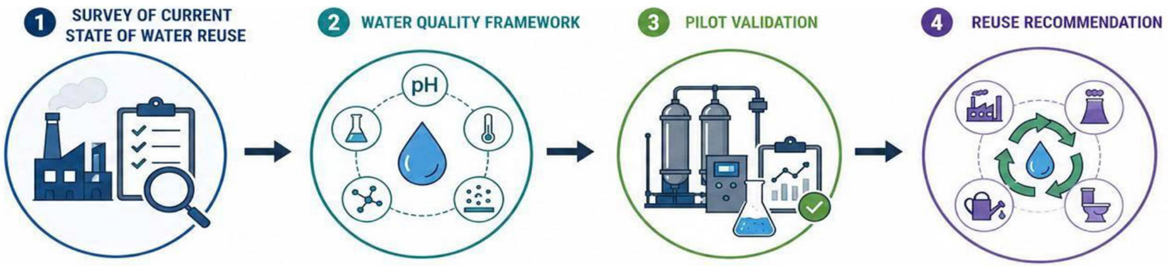

Figure 1. Research framework

northern regions of Vietnam, and responses were received as scanned files. Businesses are concentrated in the Southern region, mainly in provinces with developed industries such as Ho Chi Minh City, Binh Duong, Dong Nai, and Tay Ninh (43/68 votes). The Central and Northern regions have 10 and 15 businesses in the industrial parks, respectively.

Developing the water reuse criteria for different purpose

Based on surveyed water reuse quality requirement from the businesses, reference of GB/T 19923 - 2005, OEKO-TEX®, ZDHC wastewater guidelines version 2.2 (2024), and DIN EN 12952-12:2003, a standard framework for water reuse in the textile industry with various reuse purposes is proposed. These water reuse criterias after proposing were feedbacked from the textile businesses through workshop.

Experimental advanced treatment of post-treatment wastewater using a pilot multi-stage membrane system

The real textile wastewater was taken from the effluent of the secondary physico-chemical settling tank of the wastewater treatment system at three companies including Thai Tuan Textile Joint Stock Company, Songwol Vina Joint Stock Company, and Phuc Toan Thinh Production and Trading Company Limited. Three representative textile enterprises were selected using purposive sampling to cover major production types in the Vietnamese textile industry. The selection criteria included differences in raw materials, textile products, manufacturing processes, production scale, and wastewater characteristics. Songwol Vina manufactures cotton towels and bath sponges with dyeing operations; Thai Tuan produces polyester, TC, TR, and spandex-based fabrics through dyeing and printing processes; and Phuc Toan Thinh manufactures polyester knitted fabrics involving knitting and dyeing. These factories represent three typical textile production categories that generate wastewater with different pollutant compositions and treatment challenges. Although the selected enterprises cannot fully represent the entire Vietnamese textile industry, they provide a practical range of wastewater characteristics for evaluating the applicability of different membrane treatment configurations under representative industrial conditions.

The experimental pilot system was set up as Figure 2. In this study, wastewater input were supplied into the MF+UF system with 2.0 L/min; MF+UF+NF with 1.7 L/min, and MF+UF+RO with 8.0 L/min.

MF had 3 levels, including 10-5-1 μm, polypropylene, maximum capacity of 300 L/h, maximum pressure of 72 PSI (5 bar), and made in Taiwan. UF had a maximum capacity of 100 L/h, a maximum pressure of 120 PSI (8,3 bar), and made in Korea. RO was model TW30-1812-50HR Dow Filmtec (10 liters), maximum capacity of 8 L/h, maximum pressure of 150 PSI (10,3 bar), filter material of polyamide, and made in the USA.

Pressure operation: MF+UF system: maximum 4 bar (58 PSI); MF+UF+NF system: maximum 7 bar (101 PSI); MF+UF+RO system: maximum 7 bar (101 PSI). Operating on the isoflow principle, backwashing occurs when the NF/RO flow rate drops below 80% of the design flow rate. Permeate/Concentrate ratio of the NF and RO system was 80/20 and 60/40, respectively.

Each experiment was repeated 5 times, while the MF+UF+RO model was repeated 12 times. Wastewater before and after treating were taken, preserved, and analyzed by the Southern Environmental Monitoring Center. Each sample was analyzed three times.The selected water quality parameters including pH, color, hardness, turbidity, iron, electrical conductivity, and total suspended

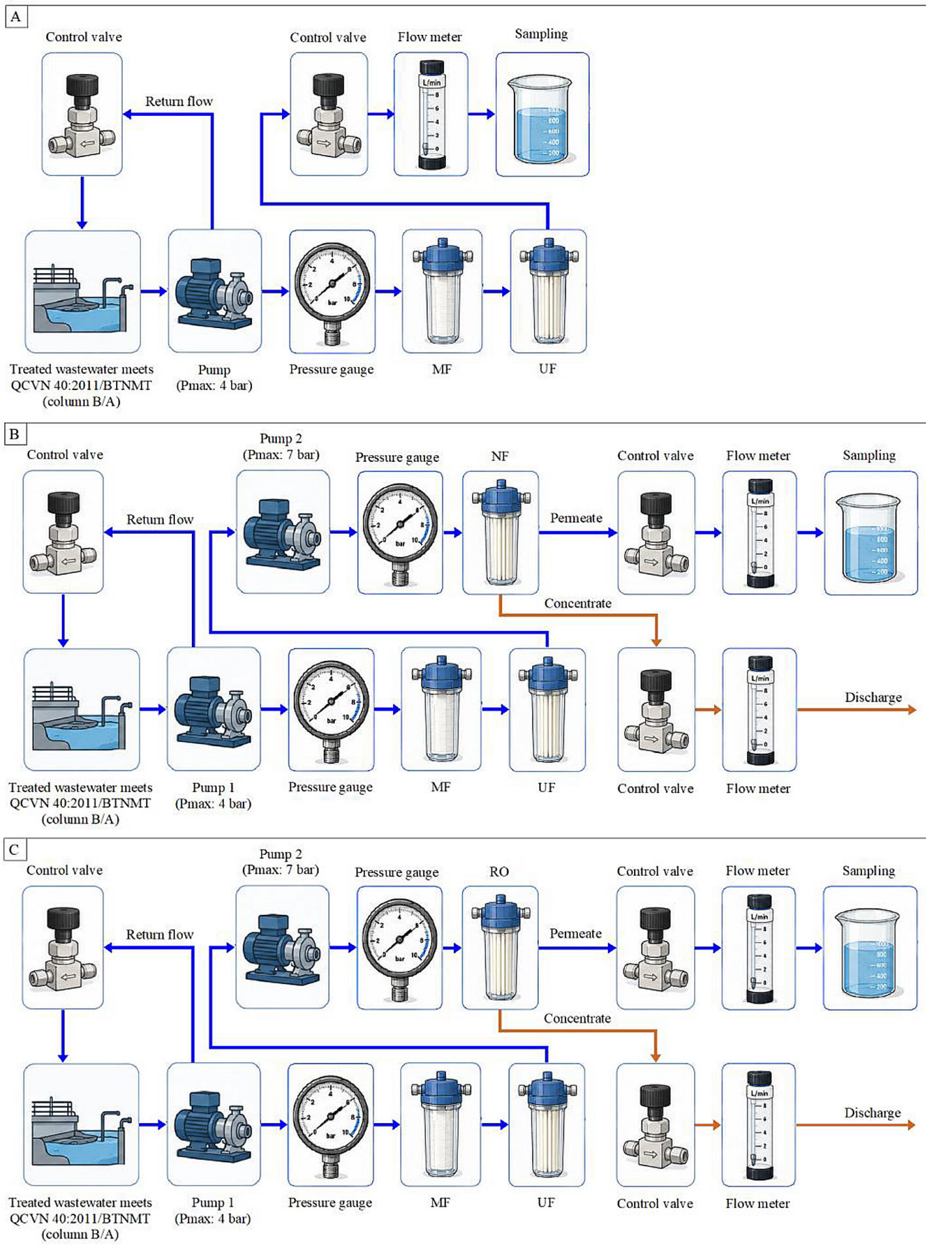

Figure 2. Diagrams of pilot multi-stage membrane system MF+UF (A), MF+UF+NF (B), and MF+UF+RO (C)

solids, were chosen because they directly influence the feasibility of wastewater reuse in textile dyeing processes rather than merely reflecting pollutant removal efficiency. pH affects dye fixation and chemical reactions during dyeing, while TSS and turbidity indicate the presence of suspended particles that may cause fabric defects and equipment fouling. Color is a critical parameter because residual dyes can alter subsequent dyeing operations. Electrical conductivity represents the accumulation of dissolved salts that influence dye uptake and process chemistry, whereas hardness (Ca^{2+} and Mg^{2+}) may cause scaling and interfere with dyeing auxiliaries. Iron was included because dissolved iron can form colored complexes with dyes and produce staining on fabrics (Table 1).

RESULTS AND DISCUSSION

The current of water reuse at textile factories in Vietnam

The results of 68 surveyed companies showed that woven fabric products are the most produced type, accounting for 38.24%; garment manufacturing accounts for 26.47%, mainly concentrated in the Central and Northern regions. Fabric and

Table 1. The instrument errors and method limitations

No.	Parameter	Unit	Equipment error	LOD
1	Temperature[(c)]	°C	±0.4 °C	-20.0 to 120 °C
2	pH[(c)]	-	±0.01 pH	-2.00 to 16.00
3	Colour[(c)]	Pt–Co		5 Pt-Co
4	Hardness[(c)]	mg/L		2 mg/L
5	Turbidity[(c)]	NTU		0.02 NTU
6	EC [(c)]	µS/cm	±2%	10 mg/L (TDS)
7	TSS[(b)]	mg/L		5 mg/L
8	Iron (Fe)[(b)]	mg/L		0.03 mg/L

Note: Electrical conductivity and TDS were exchanged by the equation: TDS (mg/L) = K*EC (µS/cm), with K = 0.64.

yarn production accounts for 16.18%; yarn production alone accounts for 10.29%; and specialized fabric and yarn dyeing accounts for 8.82%. Companies producing auxiliary and other products are very few, only 5.88% each. The majority of surveyed companies have a dyeing step in their production process, accounting for 69.12%. Of these, 6 businesses specialize in dyeing yarn and fabric, 12.76%, mainly concentrated in the Southern region. For the remainder, dyeing is a step in the yarn and fabric production process. Only 29.41% of businesses have a printing step in their production process; most companies do not have a printing step.

The survey results on water consumption indecated that 39.71% of businesses require more than 3000 m^3/day, all of which have dyeing processes in their production. The business with the highest water demand reached 40,000 m^3/day. The businesses surveyed had the second highest water demand at 12,635.8 m^3/day and 12,655 m^3/day respectively. Six businesses had water flow rates ranging from 6.000 m^3/day to 8.561 m^3/day. According to the survey results on water usage norms, the water usage per square meter of fabric varied greatly depending on the product type and production technology, from 1.3 liters/m^2 to 90 liters/m^2. The highest water usage norm was approximately 90 liters/m^2 when producing cotton towels with dyeing. For facilities that only produce yarn without dyeing/printing processes, the water usage was low, mainly domestic wastewater, only about 1.3–11.15 liters/m^2. When only weaving fabric, the standard water consumption is approximately 2.6 liters/m^2. Other surveyed businesses produce many different types of products, therefore determining the water consumption standard for each individual product is very difficult. The amount of wastewater generated and discharged accounts for 25–100%, depending on the water reuse rate of the enterprise. Specifically, 29.85% of enterprises have a wastewater generation rate of 90–100% of their water supply, 35.8% have a rate of 80–90%, 11.9% have a wastewater generation rate of 70–80%, 14.92% have a rate of 50–70%, and 7.46% have a wastewater generation rate of less than 50% of their water supply.

The reuse of treated wastewater as an alternative water source to other natural water sources is encouraged, and preferential treatment is stipulated in Article 59 of the 2023 Water Resources Law. The textile and garment industry is one of the industries that consumes a large amount of water and generates a lot of wastewater, so it has great potential for implementing water recycling and reuse. A survey of 68 businesses in Vietnam shows that the percentage of businesses reusing water is still low, only 38.24% (26/68). Businesses reuse water due to customer requirements and voluntarily save water. This also indicates that water reuse has not been given sufficient attention in businesses within the textile and garment industry. Of the 26 businesses that reuse water, 50% have a reuse volume exceeding 1000 m^3/day. Ten units reused less than 1000 m^3/day, accounting for 38.46%, and three units had an undetermined reuse volume.

However, in terms of the rate of reuse of treated wastewater compared to the total water supply demand, this rate is still low. Approximately 7.46% of enterprises have a water reuse rate >50%, of which only one enterprise reuses up to 93.45% of its water supply demand, and one enterprise reuses 76% of its total water supply demand. The most common reuse rate is below 50% of water supply demand, mainly below 30%, accounting for 11.9%. The reuse rate between 30% and 50% of water demand is 14.92%. Businesses reuse water typically for some purposes such as cleaning factory premises, sanitizing equipment, and production activities like bleaching, dyeing, and weaving,... This rate indicated that current water reuse rate in Vietnamese businesses is lower than in China or Bangladesh, where many businesses achieve 70–90% water reuse [8, 9]. This also means that the potential for water reuse in the textile industry is still very large, including the possibility of reusing water in businesses that do not yet have water reuse activities and increasing the reuse rate in existing businesses.

Of the 26 businesses involved in water reuse, 80.77% have their own treatment systems or advanced treatment stages to support reuse activities (21/26 businesses). A portion of the water after conventional wastewater treatment (with output meeting Column B or Column A according to QCVN 40:2011/BTNMT) is further processed through a reuse treatment system before being reused. Businesses with complete reuse treatment systems have a wider reuse scope, including use for production purposes. The remaining businesses directly reuse water after conventional wastewater treatment (reached Column B or Column A according to QCVN 40:2011/BTNMT). These businesses mainly reuse water for factory cleaning, equipment cleaning, and toilet flushing. The water reuse treatment technologies used in water treatment systems at the surveyed enterprises are quite diverse, including sand filtration, UF

Table 2. Current status of water reuse at 26 surveyed companies that reuse water

No	Company	Water use / water demand	Water reuse treatment system	Water reuse quality requirement	Reuse purpose													
					Factory cleaning	*Dyeing*	*Wa-shing*	*Chemicals dilution*	*Flu-shing the toilet*	*Weight*	*Product comple-tion*	*Cooling*	*APC*	*BW*	*Watering the charcoal*	*Produ-ction*	*Degre-asing, ble-aching*	*Not specified*
1	Da Luen	20/3362			√										√			
2	Hualon Corporation	7000/13000	√													√		
3	Grand Textile	1160/1370	√		√	√				√				√				
4	Chain Yarn	2000/8446	√															√
5	New Wide	1100/7968	√	√		√												
6	Gain Lucky	10000/40000														√		
7	Thanh Cong (TCG)	1200/3510	√			√												
8	Huge Bamboo	1895/3930	√	√	√	√	√	√										
9	Polytex Far Eastern	7000/11628	√		√	√												
10	Chanco	2000/4280	√	√		√			√			√	√				√	
11	De Licacy	2550/8700		√						√								
12	Hyosung	Not specified																√
13	Paihong	1000/2175	√	√		√	√									√		
14	Paiho	500/1351	√													√		√
15	Promax	8000/8561	√													√		
16	Hai Minh	3000/6399		√	√	√												
17	Juzchen	700/2000					√		√									
18	Pacific Crystal	273/5000	√			√							√					
19	Delta Galil	725.67/1432			√				√							√		
20	PNS Chun	996/1466	√	√														
21	XDD Textile	400/3400				√					√							
22	Ha Bac																	√
23	TMVS	2/1000		√					√									
24	Kim Long	30/400						√										
25	Nien Hsing	250/2567							√				√					
26	TCE Vina Denim	342/4026		√			√											

Note: APC – Air pollution control, BW – backwash in water treatment system.

filtration, RO, activated carbon adsorption, ion exchange, and advanced oxidation…Only 9 out of 21 businesses with water reuse treatment systems (42.86%) had specific water reuse quality requirements (Table 2 and Table 3).

Water reuse quality framework were suggested based on water reuse quality requirements from the businesses, GB/T 19923 - 2005, OEKO-TEX®, ZDHC wastewater guidelines version 2.2 (2024), DIN EN 12952-12:2003, and opinions of businesses at the workshop. The complete water reuse standard framework is divided into 4 levels including level 1 is water reuse for boilers, level 2 is waster reuse for high-quality processes such as bleaching, light dyeing, and high-end export products, level 3 is water reuse for general processes such as washing, rinsing, medium dyeing, and basic finishing, and level 4 is water reuse for less demanding processes such as cooling, equipment cleaning, air pollution control and factory cleaning (Table 4).

Assess water reuse potential after treating by multi-stage membrane

Water reuse potential was assessed after treating by MF+UF, MF+UF+NF, and MF+UF+RO pilots with the effluent from the secondary

Table 3. Water reuse quality requirement from the surveyed businesses

No.	Parameter	Unit	Requirements for the quality of water reuse in businesses										
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)	(10)
			Factory cleaning, dyeing	Factory cleaning, washing, dyeing	Dyeing, Air pollution control	All purpose, except drinking, cooking	Weight, washing	Dyeing, bleaching, air pollution control, cooling, flushing toilet	Dyeing	Dyeing	Equipment cleaning, washing	Weight	Production stages
1	pH	-	5.5–8.5	6.0–8.5	7–8.5	5.5–6.5	6.5–8.5	6.5–8.5	7–8	7–8	6–9	6–9	6.5–7.4
2	Turbidity	NTU	0.2	2	-	-	-	2	30	30	-	-	3–5
3	Hardness	mg $CaCO_3$/L	20	300	3	5	-	171	10	10	-	-	53
4	Amonia	mg/L	-	1	-	-	-	3	-	-	5	-	0.05
5	Nitrate	mg/L	-	11	-	-	-	50	-	-	-	-	0.5
6	Iron	mg/L	-	0.3	-	-	0.05	0.3	-	-	1	-	0.1
7	COD	mg/L	-	2	-	10	-	-	-	-	75	100	-
8	SS	mg/L	-	-	-	-	-	-	-	-	50	35	-
9	Grease	mg/L	-	-	-	-	-	-	-	-	5	10	-
10	Colour	Pt-Co	10	15	-	-	1	-	10	10	50	50	20
11	TDS	mg/L	-	1.000	-	50	-	-	-	-	-	-	150
12	Cl^-	mg/L	250	300	170	-	200	-	-	-	500	-	25
13	Alkalinity	mg/L	-	-	-	10	-	-	-	-	-	-	35
14	Sunfate	mg/L	-	250	-	-	-	-	-	-	-	-	30
15	Mn^{2+}	mg/L	-	0.1	-	-	-	-	-	-	0,5	-	0.1
16	Mg^{2+}	mg/L	-	-	-	-	-	-	-	-	-	-	2
17	Ca^{2+}	mg/L	-	-	-	-	-	-	-	-	-	-	20
18	SiO_2	mg/L	-	-	-	1	-	-	-	-	-	-	30
19	Conductivity	µS/cm	-	-	450	-	-	-	400	400	-	-	-

Note: (1): Survey information from Hai Minh Textile and Dyeing Joint Stock Company, Ninh Binh; (2): Survey information from Junzhen Garment Co., Ltd., Ninh Binh; (3): Survey information from Pacific Crystal Textile Co., Ltd., Hai Phong; (4): Survey information from Delta Galil Vietnam Co., Ltd., Gia Lai; (5): Survey information from PNS Chun Co., Ltd., Quang Ngai; (6): Water quality standards for production stages according to the technical description of the water reuse treatment plant of Chanco Industrial Co., Ltd; (7): Water treatment standards for production use at New Wide (Vietnam) Co., Ltd.; (8): Water quality requirements for the dyeing stage at Huge-Bamboo Textile Industry Co., Ltd.; (9): Water quality requirements for reuse in textile production at De Licacy Vietnam Industrial Co., Ltd.; (10): Water quality requirements after the water reuse treatment plant Using Paihong Vietnam Co., Ltd.

Table 4. Proposed framework for water quality standards for the textile and garment industry in Vietnam

No.	Parameter	Unit	Suggested values for the levels			
			Level 4	Level 3	Level 2	Level 1
1	pH	-	6.0–9.0	6.5–8.5	6.5–7.5	7.0–10.5*
2	SS	mg/L	< 100	< 50	< 10	-
3	Color	Pt-Co	< 150	< 150	< 50	-
4	Conductivity	μS/cm	-	< 1500	< 800	-
5	Total hardness ($CaCO_3$)	mg/L	-	< 100	< 50	< 30** (< 40)
6	Total iron (Fe)	mg/L	< 5	< 0.3		(***)
7	Manganese (Mn)	mg/L	< 1	< 0.1		-
8	Copper (Cu)	mg/L	< 2	< 0.3		-
9	Turbidity	NTU	-	< 10	< 5	< 30*
10	DO	mg/L	-	-	-	< 0.05** (< 0.1)
11	Cloride (Cl^-)	mg/L	< 1000	< 200	< 100	-
12	Sulfate (SO_4^{2-})	mg/L	< 300	< 200	< 150	
13	Grease	mg/L	< 10	< 1	< 0.5	
14	Residual Clorine	mg/L	< 2	< 0.1		

Note: * : All boilers in textile enterprises operate at a working pressure of < 9.18 kgf/cm^2; ** : Used for boilers using liquid or gaseous fuels. Values in parentheses apply to other fuel types; *** : Not specified for boilers with a working pressure of ≤ 9.18 kgf/cm^2 (according to TCVN 7704:2007).

physico-chemical settling tank of the wastewater treatment system at three companies including Thai Tuan Textile Joint Stock Company, Songwol Vina Joint Stock Company, and Phuc Toan Thinh Production and Trading Company Limited. Water reuse potential was determined based on comparation of pH, color, hardness, TSS, turbidity, conductivity, total suspended solid and total iron values in the effluent with water reuse quality suggested in Table 3 above. These parameters have directly affected to dyeing process throught color quality, product uniformity, effective color capture, and equipment lifespan. The values presented in this study is the average values. The characteristics of influent wastewater were presented in Table 5.

The results indicated that characteristics of treated wastewater effluent from the secondary physicochemical settling tank were very different between the three businesses, particularly in terms of color and electrical conductivity. Songwol Vina had the highest EC (4445.8 ± 340.4 mg/L), whereas Phuc Toan Thinh showed the highest color (87.83 ± 12.69 Pt-Co). These differences can be attributed to variations in production processes, dye formulations, chemical consumption, salt addition during dyeing, and wastewater treatment configurations [3]. Large quantities of NaCl and Na_2SO_4 are commonly used in textile dyeing processes to improve dye fixation, leading to elevated salinity in the treated effluent [3].

Figure 3 shows that pH was insignificant various throught all membrane stages, approximately oscillating between 6.8 and 7.6, falling within the range of all proposed water quality levels for reuse. This demonstrates that the MF, UF, NF, and RO processes are primarily physical separation processes, with no chemical reactions occurring that alter the acid-base balance of water. Output neutral pH is an advantage of membrane technology because it reduces chemical consumption to adjust pH after treatment. Besides, it limits equipment corrosion, and it facilitates reuse in textile dyeing production. The results are consistent with many previous studies showing that membrane systems hardly alter the pH of the treated water [2, 4, 6].

Color decreased significantly after each membrane stage. In all three businesses, the results showed that MF+UF removed the colorants insignificantly. After NF, the color decreased slightly, and after RO, the color was almost completely gone (Figure 4). Both the NF and RO water output reached the color limits for the high reuse levels in the proposed standard table. Color degradation results from multiple mechanisms such as retention of large-molecule dyes, and removal of dissolved organic matter. The substantial color removal observed after NF and RO suggests that most residual color compounds in the secondary

Table 5. Characteristics of the real wastewater after the secondary physico-chemical settling tank

No.	Parameter	Unit	Value		
			Thai Tuan	Songwol Vina	Phuc Toan Thinh
1	Temperature[(c)]	°C	31.7–33.8	29.9–32	31.7–35.5
2	pH[(c)]	-	7.73±0.3	7.77±0.29	7.42±0.12
3	Colour[(c)]	Pt–Co	20.17 ± 3.76	45 ± 8.88	87.83±12.69
4	Hardness[(c)]	mg/L	54.21 ± 3.34	58.4 ± 0.89	48.27 ± 3.49
5	Turbidity[(c)]	NTU	1.21 ± 0.17	1.1 ± 0.06	1.07 ± 0.29
6	EC [(c)]	mg/L	1321±146.4	4445.8±340.4	1778.8±154
7	TSS[(b)]	mg/L	Undetected	Undetected	Undetected – 19
8	Iron (Fe)[(b)]	mg/L	Undetected – 0.126	Undetected – 0.286	Undetected – 0.14

effluent were present in dissolved forms rather than as suspended particles. Reactive dyes and their degradation products generally possess molecular weights ranging from several hundred to several thousand Daltons, which are effectively retained by NF and RO membranes through size exclusion and electrostatic repulsion mechanisms [5]. RO is the most efficient due to its smallest membrane pore size and solution-diffusion mechanism. The nearly complete decolorization after RO indicates that the treated water can be reused in high-quality applications such as fabric washing and dyeing processes without causing color interference or product defects. This demonstrates that the combination of MF+UF+NF or MF+UF+RO is an effective solution for high-quality water reuse in the textile industry [1, 2, 4].

Total hardness decreased progressively with each membrane stage (Figure 5). MF and UF had almost no significant effect on hardness because Ca^{2+} and Mg^{2+} exist as dissolved ions. A noticeable reduction occurred in NF and especially in RO. After RO, hardness was consistently below the recommended limit for boiler feedwater and high-quality production water. This is entirely consistent with the mechanisms of NF and RO, where NF removes most divalent ions and RO removes almost all dissolved ions [1,4,10]. The significant reduction in hardness after NF and RO is particularly beneficial for textile industries because calcium and magnesium ions can react with dyes, detergents, and surfactants, reducing dye fixation efficiency and causing deposits on fabrics and process equipment. The low hardness achieved after RO also indicates a lower risk of scaling on boilers and heat exchangers, thereby reducing maintenance requirements and prolonging equipment lifespan [2].

Turbidity decreased very rapidly after MF+UF and continued to decrease in NF and RO. After RO, turbidity was almost zero for all three cases. All samples after NF and RO were significantly lower than the limits for reusable water (Figure 5). MF and UF play a crucial role in removing suspended solids, colloidal particles, and microorganisms. NF and RO further remove smaller particles. Low turbidity also contributes to reduced fouling risk in RO, increasing membrane lifespan [2, 11].

The high EC observed in the influent, particularly for Songwol Vina, is typical of textile wastewater because large amounts of inorganic salts are used during dyeing and finishing operations [3]. Electrical conductivity changed very little after MF and UF but decreased sharply after NF and especially after RO (Figure 5). This demonstrated that MF and UF did not remove dissolved salts. It confirmed that dissolved salts cannot be removed by low-pressure membranes. NF removed some ions, and RO removed most dissolved solids due to their ability to reject dissolved ions in high – pressure operation. After RO, EC reached a level that meets the standards for water reuse requiring high quality. Low electrical conductivity is particularly important for dyeing, chemical mixing, steam production, and finishing processes because excessive salinity may alter dye uptake, increase chemical consumption, and adversely affect the quality of textile products [1, 2, 6, 10]. So, the results demonstrated the necessity of incorporating NF or RO into water reclamation systems intended for high-quality reuse applications.

The total iron content decreases continuously through each membrane stage. After RO, Fe is only about 0.1–0.2 mg/L, meeting the requirements for water reuse (Figure 5). Iron exists in the form of colloidal particles, hydroxides, and

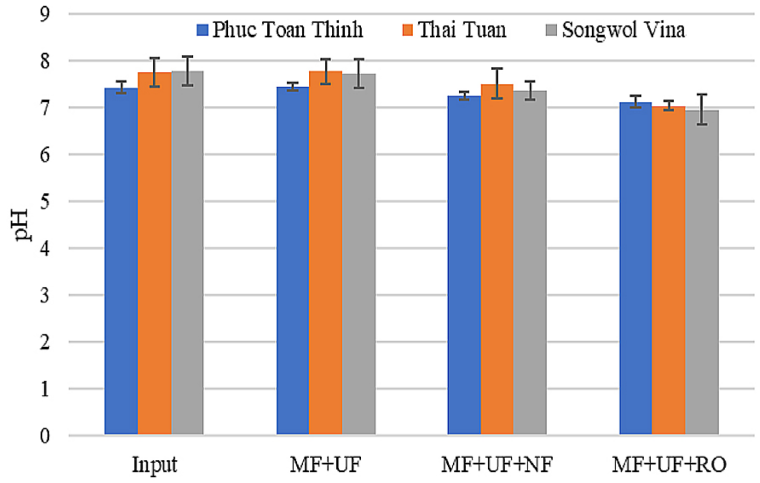

Figure 3. pH various after multi-stage membrane system

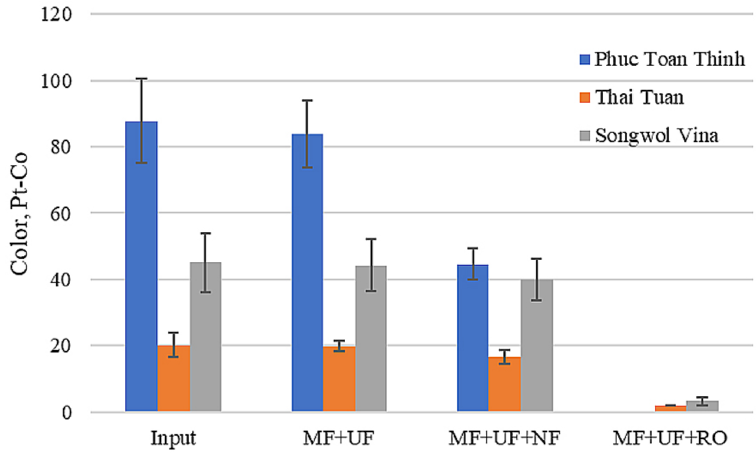

Figure 4. Color various after multi-stage membrane system

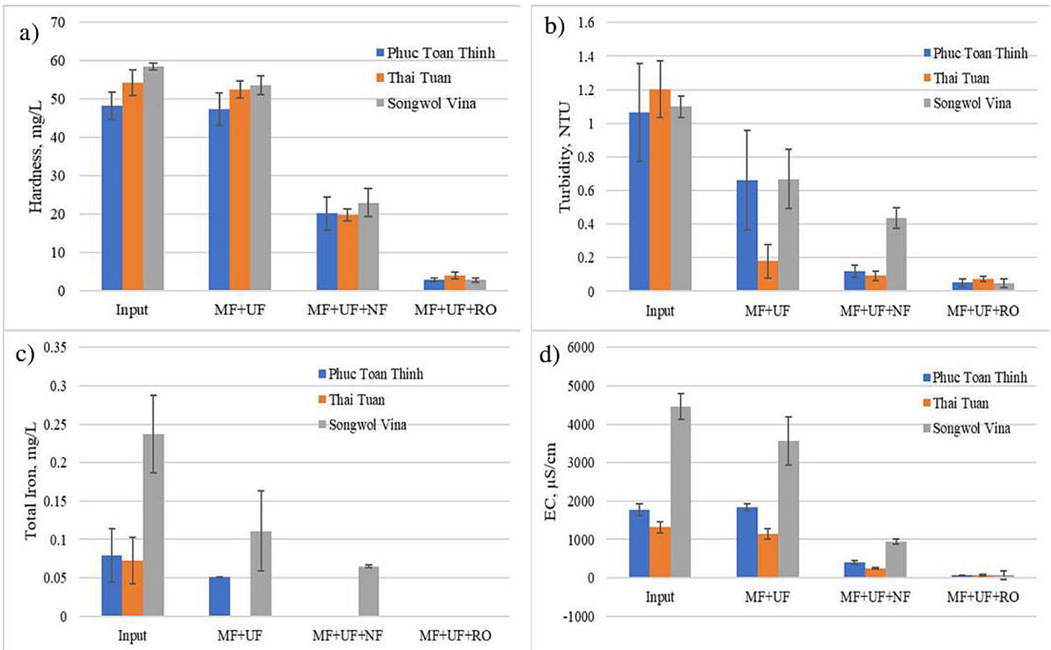

Figure 5. Hardness (a), turbidity (b), total iron (c), and EC (d) various after multi-stage membrane system

dissolved ions. Therefore, MF removes large particles, NF retains some ions, and RO removes almost all dissolved Fe. Although the initial iron concentrations were relatively low, further reduction through membrane treatment remains important because even small amounts of iron can cause discoloration of fabrics and interfere with certain dyeing processes [2, 6]. The low iron concentration obtained after RO indicated that the water output is suitable for reuse in applications requiring high water quality.

TSS was not detected after the membrane system. This demonstrates the very high efficiency of MF and UF in removing suspended solids. This result is consistent with the operating principle of MF and UF membranes, where the membrane pore size is significantly smaller than the size of suspended particles. The complete removal of TSS also helps reduce fouling in NF and RO systems, improving long-term operating efficiency and enhancing the quality of reused water (Table 6) [2, 11].

One-way ANOVA showed statistically significant differences ($p < 0.05$) among the three membrane configurations for pH, color, hardness, electrical conductivity, and turbidity. These results demonstrate that progressively tighter membrane processes significantly improve reclaimed water quality, supporting the proposed selection of membrane configurations for different reuse purposes.

Overall, the integrated MF+UF+NF or MF+UF+RO membrane system significantly improved the quality of secondary textile wastewater. Color, hardness, turbidity, electrical conductivity, total iron, and suspended solids were progressively reduced after each membrane stage, whereas pH remained relatively stable. The RO permeate exhibited the highest water quality and complied with the proposed Vietnamese textile water reuse standards for most industrial reuse applications. These results demonstrate that the multi-stage membrane process is a promising solution for water reclamation and circular water management in the textile industry (Table 7).

The pressure was observed during operation period. The results showed that the pressure increased but did not reached the limit pressure.

Although the pilot-scale experiments demonstrated the feasibility of different membrane configurations for textile wastewater reuse, several limitations should be acknowledged. First, the pilot system was evaluated using wastewater collected from three representative textile enterprises, which may not fully capture the diversity of wastewater characteristics across the Vietnamese textile industry. Second, the study focused on water quality improvement and reuse feasibility

Table 6. ANOVA analysis results

Parameter	Phuc Toan Thinh			Thai Tuan			Songwol Vina		
	F	*P-value*	*Significant difference*	*F*	*P-value*	*Significant difference*	*F*	*P-value*	*Significant difference*
pH	8.97	0.004	yes	11.74	0.0015	yes	4.61	0.032	yes
Color	214.39	4×10^{-10}	yes	208.02	4.8×10^{-10}	yes	75.3	1.6×10^{-7}	yes
Hardness	203.7	5×10^{-10}	yes	940.41	6.5×10^{-14}	yes	502.4	2.7×10^{-12}	yes
Turbidity	18.83	0.0002	yes	4.48	0.035	yes	39.03	5.6×10^{-6}	yes
EC	1253	1×10^{-14}	yes	274.07	9.7×10^{-11}	yes	122.7	1×10^{-8}	yes

Table 7. Removal efficiency and suitable water reuse level of the integrated membrane system

Parameter	MF+UF		MF+UF+NF		MF+UF+RO	
	Removal efficiency, %	*Suitable reuse level*	*Removal efficiency, %*	*Suitable reuse level*	*Removal efficiency, %*	*Suitable reuse level*
Color	5.97–8.24	4	14.9–50.8	1–4	97.87 - 100	1–4
Hardness	1.6–8.2	3, 4	57.7–64	1–4	93.6 – 95.2	1–4
Turbidity	40.3–85.55	1–4	60.9–92.2	1–4	93.6 – 95.4	1–4
EC	0.39–21.24	4	77.6–82	3, 4	94.3 – 97.4	1–4
Total iron	30.13–100	1–4	100	1–4	100	1–4
TSS	100	1–4	100	1–4	100	1–4

under pilot operating conditions, whereas long-term membrane performance, including fouling development, membrane cleaning frequency, permeate flux decline, and membrane lifespan, was beyond the scope of this study. Finally, although replicate measurements were performed for water quality analyses, extended operational stability under continuous industrial conditions was not investigated. Future studies should evaluate long-term membrane performance and economic feasibility under continuous full-scale operation to further validate the proposed reuse framework.

CONCLUSIONS

Only 38.24% of 68 surveyed textile businesses in Vietnam currently practice water reuse, and most reuse rates remain below 50% of total water demand, indicating substantial potential for water recycling. A four-level water reuse framework was developed to support different industrial reuse purposes. Pilot-scale experiments demonstrated that the integrated MF+UF+NF and MF+UF+RO systems effectively improved the quality of secondary treated textile wastewater, with RO permeate reached the proposed criteria for most reuse applications. The proposed framework and membrane system provide a practical approach for promoting wastewater reclamation and sustainable water management in the Vietnamese textile industry.

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