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Process based assessment of wastewater quality and rinse water reuse potential in denim finishing: a scalable framework for circular water management

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Industrial textile production is a significant contributor to freshwater pollution, particularly in water-intensive processes such as denim finishing. This study presents a process-based assessment of wastewater quality and rinse-water reuse potential using a stage-specific Water Quality Index (WQI) framework. By analyzing effluents from six major denim finishing stages, critical pollution hotspots were identified, and the feasibility of cascading rinse-water recovery was evaluated. Results demonstrate that WQI values decreased significantly after rinsing, with reductions reaching up to approximately 70% depending on the process stage. Furthermore, the proposed stepwise reuse strategy has the potential to reduce freshwater consumption by nearly two-thirds while maintaining operational performance. Beyond a site-specific application, the proposed methodology offers a transferable framework for industrial water optimization and circular water management in textile facilities globally. The findings contribute to advancing sustainable industrial practices and support progress toward SDG 6 and SDG 12.

Keywords Denim finishing, Wastewater reuse, Water quality index, Circular water management, Sustainable development goals

The textile industry represents one of the main pillars of the Tunisian economy, and ranks as the country's second-largest export sector[1]. Despite its economic importance, the sector is also one of the most resource-intensive and environmentally challenging industries worldwide. Denim finishing, in particular, requires large volumes of freshwater and generates effluents with complex and highly polluted compositions[2]. Typical finishing operations—including dyeing, stonewashing, bleaching, and soaping—require diverse chemicals, surfactants, and auxiliaries that produce wastewater enriched with suspended solids, dyes, salts, and organic matter[3,4]. When discharged without effective treatment, these effluents contribute to oxygen depletion, color pollution, eutrophication, and toxicity in aquatic environments[5,6]. In Tunisia, industrial wastewater discharges are regulated under national standards NT 106–002 (for discharge into the natural environment or sewer networks) and NT 106–003 (for treated wastewater intended for agricultural reuse). These standards define the permissible pollutant limits for effluents discharged into receiving environments, including rivers, coastal waters, and public sewer networks managed by the National Sanitation Office (ONAS). Developed by the National Institute for Standardization and Industrial Property (INNORPI) and enforced by ONAS, they constitute the legal framework governing industrial wastewater discharge quality. Although compliance is mandatory, it remains challenging for textile manufacturers due to the complexity and fluctuating nature of their effluents[7,8]. Conventional end-of-pipe treatments, such as coagulation–flocculation and activated sludge systems, often fail to achieve complete contaminant removal and are associated with high operational costs and sludge production[9,10]. These limitations have accelerated the transition toward source-oriented approaches, including process optimization, cleaner production strategies, and in-plant water recycling, as key components of circular water management in the textile sector[11,12].

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A process-level characterization of wastewater streams is essential for designing targeted treatment strategies and identifying effluents with strong reuse potential. While several studies have assessed composite textile wastewater[4,13], research on segregated, process-specific effluents— especially from denim finishing—remains limited. This gap is especially relevant in Tunisia, where water scarcity, increasing treatment costs, and stricter environmental regulations highlight the need for efficient water reuse strategies. Recent literature highlights a global shift toward integrated water management in textile manufacturing, emphasizing the need to close the water loop and reduce freshwater consumption[12,14–16]. Although considerable progress has been made with advanced oxidation processes, membrane filtration, and specialized microbial treatments[17,18], in-plant reuse of rinse waters remains underexplored, presenting an immediate opportunity for pollution mitigation and sustainable resource management. Previous studies have demonstrated that partial reuse of bleaching or scouring baths can substantially reduce water demand without compromising product quality[19], but a systematic assessment of rinse-water quality across the entire denim finishing chain has not yet been conducted.

This study addresses this research gap by providing a comprehensive, process-specific characterization of wastewater generated from six major denim operations— dyeing preparation, dyeing, stonewashing, bleaching, neutralization, and soaping—at an industrial facility in Tunisia. Key physicochemical parameters including pH, total suspended solids (TSS), chemical oxygen demand (COD), total dissolved solids (TDS), electrical conductivity and color were monitored and integrated into a Water Quality Index (WQI) framework to evaluate effluent quality and reuse potential. For the first time in Tunisia, this work establishes a WQI-based hierarchy of denim wastewater streams, offering actionable insights for circular water management in textile industries. Overall, the findings contribute to a new paradigm of sustainable denim manufacturing in which process-integrated water reuse serves as a foundation for cleaner production, reduced freshwater dependency, and environmental stewardship—advancing the objectives of the United Nations Sustainable Development Goals (SDG 6: Clean Water and Sanitation; SDG 12: Responsible Consumption and Production).

This study introduces a process-specific evaluation framework for denim finishing operations. Unlike previous studies that assess effluents collectively at the plant level, this work applies a stage-by-stage Water Quality Index (WQI) approach to identify critical pollution hotspots and quantify reuse feasibility. Furthermore, it demonstrates the technical viability of cascading rinse-water recovery as a scalable circular water management strategy. The proposed framework is transferable to denim finishing facilities worldwide, particularly in water-stressed regions, and provides a decision-support tool for improving industrial water sustainability. While previous studies have largely focused on composite textile wastewater or end-of-pipe treatment performance, the present work adopts a process-specific and stage-resolved approach to assessing denim effluents. By combining detailed effluent characterization with a Water Quality Index (WQI)-based evaluation, this study identifies pollution hotspots and assesses reuse potential at each stage of production. Furthermore, the proposed cascading rinse-water reuse strategy connects water quality assessment with operational water management, providing a practical and transferable approach for circular water use within the textile industry.

Materials and methods

Presentation of site

The study was conducted at a textile company located in Tunisia, specializing in denim finishing. The textile company wastewater treatment plant is designed to treat the complex and variable effluents generated by the dyeing and washing plants. The diversity of processes (dyeing, stonewashing, bleaching, neutralization, and soaping) results in significant fluctuations in the quality (pollutant load, salinity, pH) and the quantity of wastewater. The treatment is a physico-chemical process, primarily designed to remove suspended solids, color, and a portion of the organic load. The schematic flow of the treatment is as follows in Fig. 1.

Sampling

Wastewater samples were collected from different production stages of the textile manufacturing plant located in Tunisia, to obtain a representative characterization of the effluents generated throughout the various treatment processes. For each production stage, a composite and representative sample was taken according to standardized sampling procedures to ensure the reliability and reproducibility of the analytical results. The composite samples were collected over a complete machine cycle corresponding to a single processing batch for each investigated stage. This approach allowed the samples to capture the integrated wastewater characteristics generated during the full operational sequence of the process. As the same product type and standard recipes were used during the monitoring campaign, the collected samples are considered representative of the typical effluent composition for each process stage.

In Fig. 2, the investigated processes are represented which included dyeing preparation, dyeing, stonewashing (chemical with enzyme, mechanical with pumice stone, and combined enzyme/pumice), bleaching with sodium hypochlorite, chlorine neutralization, and soaping with detergent. Each of these operations involves specific chemical reagents—such as oxidants, surfactants, enzymes, and dyes–which contribute to variability in pollutant composition and concentration. Sampling was performed weekly over a monitoring period of 7 weeks, yielding a total of 7 samples per process. This approach for the assessment of temporal variations in wastewater characteristics while ensuring that the dataset for each effluent type remained statistically representative. All collected samples were stored in clean, high-density polyethylene containers, preserved at 4 °C, and analyzed within 24 h of collection. During the monitoring campaign, the machines were operated under standard industrial conditions with comparable textile loads and typical liquor ratios used by the plant for each process stage. This ensured that the observed differences in wastewater quality were primarily associated with process-specific chemical and operational characteristics rather than dilution effects caused by variations in water-to-fabric ratios or batch size.

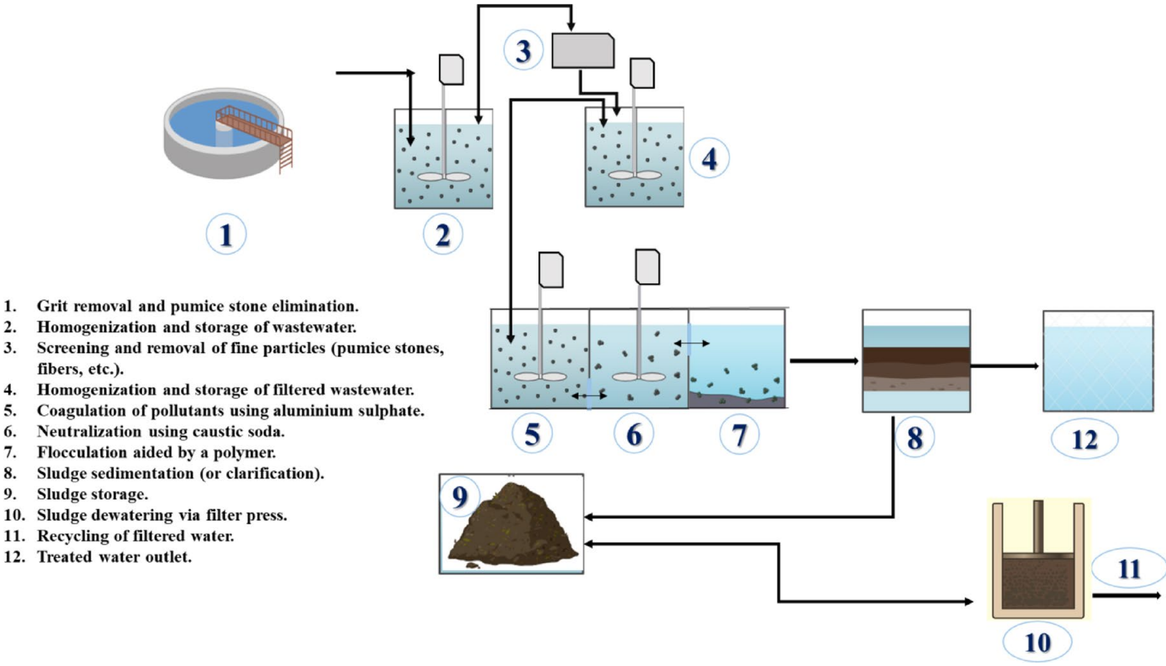

Fig. 1. Diagram of the textile company wastewater treatment plant.

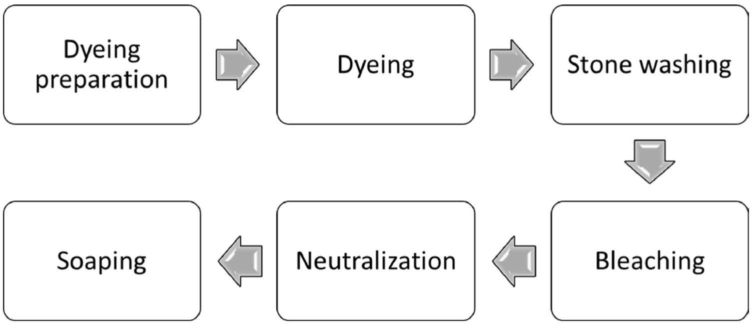

Fig. 2. Denim processing steps.

Analysis

The wastewater samples collected from the dyeing and washing unit were analyzed for their physico-chemical characteristics using standard methods. The parameters measured included pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), and color. The pH was measured using a HACH pH meter, and the conductivity and TDS were determined using a HACH conductometer. Total Suspended Solids (TSS) were determined spectrophotometrically at 810 nm using a HACH UV–Vis spectrophotometer. The method was based on a calibration curve established between absorbance and TSS concentration using standard reference suspensions, ensuring reliable quantification within the working range of the instrument. COD was analyzed by the dichromate oxidation method, and the measurement was performed using a HACH spectrophotometer at wavelengths of 420 nm (for the range 0–150 mg/L) or 620 nm (for the range 0–15.000 mg/L). Color was assessed on the Platinum-Cobalt (Pt–Co) scale using a HACH spectrophotometer at a wavelength of 465 nm. These measurements allowed for a comprehensive evaluation of the quality of wastewater from different textile processes and their compliance with Tunisian standards.

Water Quality Index (WQI) model

The Water Quality Index (WQI) is a robust tool that synthesizes multiple water quality parameters into a single, comprehensible value, facilitating the interpretation of overall water quality. While traditionally applied to surface and drinking waters, this study adapts the WQI to assess industrial textile effluents, with a novel focus on evaluating their feasibility for process-level reuse.

Five key parameters (COD, TSS, conductivity, TDS, and pH) were selected for index calculation based on their regulatory relevance and influence on reuse potential. Each parameter was normalized against its corresponding guideline value (S_n): pH (6.5–9), TSS (400 mg/L), conductivity (7000 µS/cm), TDS (5000 mg/L), and COD

(1000 mg/L), as specified in national discharge and reuse standards (NT 106.002/NT 106.003). The selection of WQI parameters was based on their regulatory significance and relevance to industrial wastewater reuse. COD and TSS were chosen as key indicators of organic pollution and suspended solids, which directly influence treatment requirements and process compatibility[10]. Conductivity and TDS were selected to represent salinity and dissolved solids, which are critical factors influencing textile processing performance and the feasibility of water reuse[20]. Although these two parameters are often correlated indicators of salinity, they were both retained because they provide complementary information regarding the ionic strength and the overall mineral content of the effluent, reflecting the contribution of different chemical inputs used during denim processing (dyes, salts, and auxiliary chemicals). pH was included due to its importance in maintaining optimal chemical conditions and compliance with discharge standards. Although additional parameters such as color and Biological Oxygen Demand (BOD) are commonly used in wastewater assessment, they were not incorporated into the WQI in this study. Color is highly process-dependent and difficult to standardize within a unified index due to the variability of dye compositions[6]. Nevertheless, it remains a critical parameter for reuse applications, particularly to prevent chromatic carry-over and should be evaluated alongside WQI results in practical decision-making. However, BOD is less representative of the recalcitrant organic compounds typically found in textile effluents.

The WQI was determined through a three-step sequential process[21]:

Step 1: Calculation of the unit weight (W_n)

Each parameter was assigned a unit weight (W_n) inversely proportional to its recommended standard value (S_n), thereby assigning greater importance to parameters with stricter limits. The unit weight was calculated as:

$$\boldsymbol{W_n} = \frac{\boldsymbol{K}}{\boldsymbol{S_n}} \tag{1}$$

where K is a proportionality constant obtained from:

$$\boldsymbol{K} = \frac{1}{\sum\left(\frac{1}{\boldsymbol{S_n}}\right)} \tag{2}$$

The calculated unit weights for each parameter are presented in Table 1.

Step 2: Determination of the quality rating (q_n)

The quality rating (q_n), or sub-index, quantifies the deviation of a parameter's measured value (V_n) from its ideal value (V_{io}). It was computed using the following equation:

$$\boldsymbol{q_n} = 100 \times \left|\frac{\boldsymbol{V_n} - \boldsymbol{V_{io}}}{\boldsymbol{S_n} - \boldsymbol{V_{io}}}\right| \tag{3}$$

For most parameters, the ideal value (V_{io}) is 0. For pH, the ideal value was taken as 7 (neutral). The pH sub-index was calculated based on its deviation from the recommended standard range, following conventional WQI formulations[22]. Owing to its relatively narrow permissible range, pH may exert a comparatively higher influence on the overall WQI, particularly when significant variations across different process stages[23]. In this study, such variations reflect actual process conditions and remain environmentally relevant, as pH plays a crucial role in governing chemical reactions and treatment efficiency[24]. To ensure a balanced interpretation, WQI results were supplemented with an analysis of individual physicochemical parameters, thereby avoiding over-reliance on any single variable.

Step 3: Computation of the overall WQI

The overall WQI was calculated by aggregating the weighted sub-indices of all parameters. The standard formula is:

$$\boldsymbol{WQI} = \frac{\sum_{n=1}^{n} \boldsymbol{q_n} \times \boldsymbol{W_n}}{\sum_{n=1}^{N} \boldsymbol{W_n}} \tag{4}$$

However, since the constant K is defined such that $K = \sum W_n = 1$, the formula simplifies to:

Parameter	Unit weight (W_n)
pH	0.974
TSS	0.017
Conductivity	0.001
COD	0.007
TDS	0.0014

Table 1. Calculated unit weights (W_n) for the selected water quality parameters.

$$\boldsymbol{WQI} = \sum_{n=1}^{n} \boldsymbol{q}_n \times \boldsymbol{W}_n \quad (5)$$

To facilitate interpretation of the wastewater quality results, the Water Quality Index (WQI) values obtained were classified according to different ranges. The classification scheme categorizes water quality into five distinct levels: excellent (0–25), good (26–50), poor (51–75), very poor (76–100) and unsuitable for industrial reuse (> 100), which provides a standardized framework for assessing the reuse potential or treatment needs of effluent streams[20,21].

The WQI classification ranges adopted in this study are commonly used for assessing surface and drinking water quality assessment. However, in the present work, these categories are not applied to evaluate potability, but rather to provide a relative framework for comparing wastewater quality across different textile processing stages. Accordingly, the WQI serves as a decision-support tool for ranking effluent streams and identifying their reuse potential. Final reuse decisions are based on an integrated assessment that combines WQI results, individual physicochemical parameters and compliance with industrial discharge and reuse standards. It's important to note that WQI results outcomes are influenced by the selection and weighting of parameters. In this study, unit weights were assigned inversely proportional to the corresponding standard limits, thereby assigning greater importance to parameters with stricter regulatory thresholds. While this approach is widely adopted, alternative weighting schemes may yield variations in the calculated WQI values. Nevertheless, a qualitative sensitivity analysis indicates that the overall ranking of effluent quality and the identification of major pollution sources remain consistent, demonstrating the robustness of the proposed WQI framework for the comparative evaluation of industrial wastewater streams.

A specific methodological adaptation was required for bleaching effluents due to the well-documented interference of high chloride concentrations (> 3 g/L) with the dichromate COD method. Under these conditions, COD measurements were not reliable and were therefore excluded from the WQI calculation exclusively for the bleaching stage, as also reported for high-chloride textile effluents[25]. In contrast, COD was successfully measured and fully incorporated into the WQI calculation for all other process stages (dyeing, stone-washing, neutralization and soaping), for which the standard condition $\sum W_n = 1$ was satisfied.

For the bleaching stage, the WQI was calculated using the remaining four parameters (pH, TSS, conductivity, and TDS). In this case, the original unit weights were retained without renormalization, resulting in a sum of weights ($\sum W_n$) lower than unity due to the exclusion of COD. This approach is consistent with previous studies indicating that WQI models can be adapted by excluding parameters when their measurement is unreliable, provided that the limitation is clearly acknowledged[22,26]. Consequently, the WQI for bleaching represents a reduced-parameter index and should be interpreted accordingly.

Results and discussion

Monitoring of discharge quality

The variation in the measurements of different quality assessment parameters of wastewater from dyeing preparation, dyeing, bleaching, stone washing, neutralization, and soaping processes was monitored over a defined period and was presented in Fig. 3. The measurements of COD, TSS, conductivity, TDS, and pH were quantified using conductometric and colorimetric methods with HACH analytical instruments in accordance with standard analytical procedures, as described in the experimental section.

Monitoring the quality of discharge from the dyeing preparation process

Dyeing preparation is a pre-treatment step that wets, cleans, and conditions the garment to enhance dye uptake and ensure uniform coloration in the subsequent dyeing process. By analyzing Fig. 3, it was observed that the evaluated parameters conformed to international textile wastewater standards[17]. Indeed, the pH values fell within the required range [6.5–9]. Moreover, the concentrations of TSS were very low, confirming that this type of effluent contains minimal particulate matter. In addition, the measured COD values were below 1000 mg/L, which is consistent with the acceptable limits for textile preparation discharges. Furthermore, the measured color units on the platinum–cobalt scale for the various preparation effluents were low, as the garments are generally prepared in white, which explains the reduced color load. This aligns with findings in textile effluent studies where color units have been reported to be significantly lower in preparation stages compared to dyeing stages[4]. Regarding the obtained electrical conductivity values, we noted that they complied with recommended limits, as they did not exceed 7000 µS/cm. Finally, TDS values were all below 5000 mg/L, confirming that the preparation effluents remain within the guideline levels reported for textile wastewater reuse.

In conclusion, the quality of dyeing preparation effluent is good. Therefore, these effluents may be reused in subsequent processes or discharged directly into the ONAS sewerage system without requiring additional treatment.

Monitoring the quality of discharge from dyeing process

The dyeing process involves fixing color onto denim articles and typically comprises three stages: preparation of the fabric, addition of the dyestuff, and subsequent introduction of an industrial salt to promote dye fixation. Based on the monitoring of dyeing discharge quality parameters shown in Fig. 3, the results reveal notable variability among the evaluated parameters, with some failing to comply with Tunisian regulatory limits (NT 106.002 and NT 106.003). Indeed, the pH values varied within the range required by the standards [6.5–9]. Furthermore, the TSS quantities were below 400 mg/L. Additionally, the measured COD values were above 1000 mg/L, confirming the high organic load typically associated with dyeing effluents, as also reported by other studies[3,27]. Consequently, the color unit on the platinum-cobalt colorimetric scale for the different

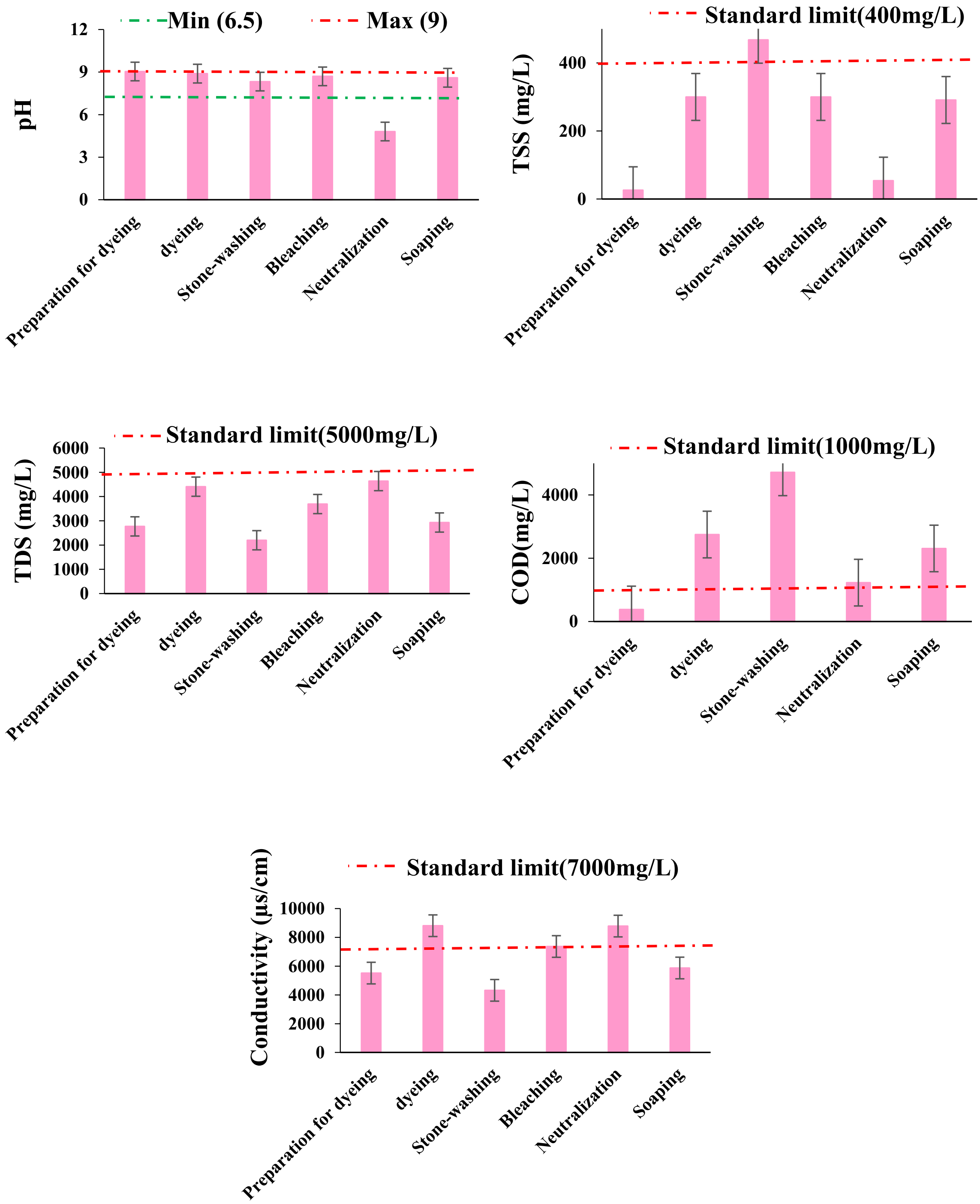

Fig. 3. Variation of key wastewater quality parameters during the different stages of the denim finishing process: preparation for dyeing, dyeing, stone-washing, bleaching, neutralization, and soaping. The parameters include pH, TSS, TDS, COD, and conductivity. Bars represent mean values and error bars indicate standard deviation. The dashed lines represent the regulatory discharge limits for each parameter (pH: 6.5–9; TSS: 400 mg/L; TDS: 5000 mg/L; COD: 1000 mg/L; conductivity: 7000 µS/cm).

dyeing discharges is high, which agrees with studies highlighting the persistence of dyes and their resistance to biodegradation[28]. Regarding the obtained electrical conductivity values, we found that they did not comply with the standards as they exceeded 7000 µS/cm, a common feature of highly saline textile wastewater. Finally, the TDS values were all below 5000 mg/L, which is the guideline level required by the standard. Accordingly, the results indicate that the dyeing effluent exhibits poor quality. All discharges from the dyeing process must undergo purification treatment to become compliant with standards, with advanced approaches such as membrane processes and reuse strategies showing promising results in Tunisia[17].

Monitoring the quality of discharge from stone washing process

Stone washing is a denim finishing treatment aimed at controlled fading and texture modification, achieved through mechanical abrasion using pumice stones or combined enzymatic/abrasive action. Analysis of the monitoring data for stone washing effluent quality parameters presented in Fig. 3 reveals significant variability throughout the study period. The recorded pH values consistently fell within the standard required range of [6.5–9]. However, all measured TSS concentrations exceeded the Tunisian regulatory guideline of 400 mg/L. Furthermore, COD values were consistently above the 1000 mg/L threshold. Stone washing effluents exhibited intense coloration, with Platinum-Cobalt (Pt–Co) color units markedly higher than those reported in most other textile wastewater studies[29]. Notably, both conductivity and TDS remained within permissible limits, measuring below 7000 μS/cm and 5000 mg/L, respectively. In conclusion, the stone washing effluent demonstrates poor overall quality and requires appropriate treatment processes to achieve regulatory compliance.

The elevated TSS and COD levels observed in stone-washing effluents can be attributed to the mechanical abrasion of denim fabric and pumice stones, which release fine particulate matter into the wastewater. In addition, the use of enzymes and surfactants contributes to the presence of biodegradable organic compounds, increasing the COD[30]. These characteristics limit the direct reuse of such effluents, as high suspended solids may interfere with subsequent processing steps and organic loads may affect process stability[10]. Notably, stone-washing processes may involve enzyme-based, pumice-based or combined treatments, each potentially generating distinct effluent characteristics in terms of suspended solids, turbidity and organic load. In this study, these sub-processes were considered collectively to represent the overall stone-washing stage under typical industrial conditions. Consequently, the reported values reflect an averaged effluent quality and variability between specific treatment types is not explicitly distinguished. Therefore, the effluent characteristics presented here should be interpreted as a generalized representation of the stone-washing stage rather than a process-specific evaluation of individual treatment modalities.

Monitoring the quality of discharge from bleaching process

Bleaching is applied to lighten denim garments by degrading indigo or sulfur dyes, producing a faded appearance characteristic of washed denim finishes. Throughout the monitoring of the variation in bleaching discharge quality parameters, we observed that the evaluated parameters displayed in Fig. 3 did not vary significantly and were almost compliant with the required Tunisian standards (NT106.002 and NT106.003). Indeed, the pH values varied within the range required by the standards. Furthermore, the TSS quantities were below 400 mg/L. Regarding COD measurements, we were unable to evaluate them. Since the chloride content measured by the Charpentier-Volhard method in the bleaching discharge was greater than 3 g/L, and above this value, the potassium dichromate measurement method is no longer applicable, as also reported in studies dealing with high-chloride bleaching effluents[31]. Consequently, the color unit on the platinum-cobalt colorimetric scale for the different bleaching discharges is variable, as this unit depends on several factors such as the quantity and color of the garments being washed. Regarding conductivity measurements, we noted that most of the obtained values complied with the standards as they were below 7000 μS/cm, except for sample 5 (S5) where the value was equal to 7370 μS/cm. Finally, the TDS values were all below 5000 mg/L, which is the guideline level required by the standard. We conclude that the quality of the bleach discharge is moderate. This discharge must undergo a purification treatment process to eliminate toxic substances originating from sodium hypochlorite, which prevented COD measurement. To overcome this limitation, alternative analytical approaches can be considered for high-chloride effluents. These include modified dichromate COD methods incorporating mercuric sulfate to complex chloride ions and reduce interference. In addition, commercially available COD test kits specifically designed for high-salinity matrices may provide more reliable measurements. Alternatively, Total Organic Carbon (TOC) can be used as a complementary parameter to estimate the organic load when COD determination is not feasible[32]. Therefore, COD values for bleaching effluents could not be reliably determined in this study.

Monitoring the quality of discharge from neutralization process

Neutralization is performed following chemical bleaching to remove residual chlorine and prevent fabric damage. This step commonly uses sodium metabisulfite as a reducing agent to quench residual oxidants. As illustrated in Fig. 3, the monitored neutralization effluent parameters exhibited relatively low variability; however, they persistently failed to meet regulatory requirements. The pH values were uniformly acidic, remaining below the regulatory threshold of 6.5. TSS concentration remained significantly low, measuring below the 400 mg/L limit. However, COD values systematically exceeded the regulatory threshold. The effluent exhibited moderate coloration, as measured in Platinum-Cobalt (Pt–Co) units. Conductivity values were non-compliant, consistently surpassing the 7000 μS/cm standard, while TDS concentrations remained within the permissible limit of 5000 mg/L. In conclusion, the neutralization process effluent demonstrates intermediate quality characteristics and requires pretreatment prior to discharge into public sewer systems to achieve full regulatory compliance. The high COD and conductivity observed in neutralization effluents are mainly associated with the use of reducing agents such as sodium metabisulfite. These compounds react with residual chlorine to form dissolved salts (sulfates and chlorides). These reactions increase ionic strength and contribute to elevated salinity levels[18]. Such chemical characteristics can limit reuse potential, as high salt concentrations and residual reducing agents may affect dye uptake and fabric quality in subsequent textile processes.

Monitoring the quality of discharge from soaping process

Soaping is a post-dyeing washing treatment using detergents to remove unfixed dye, enhance shade uniformity, and improve color fastness of the garment. Following the monitoring of the variation in soaping discharge quality parameters illustrated in Fig. 3, we observed that the evaluated parameters did not vary significantly and were almost compliant with Tunisian standards. Indeed, most pH values varied within the range [6.5–9] required by the standards, except for the first sample (S1) where the pH value was equal to 6.15. Furthermore, the TSS quantities were below 400 mg/L. Additionally, the measured COD values were all above 1000 mg/L, which is the guideline level required by the standard. Also, the platinum-cobalt color unit of the soaping discharges is high. The obtained conductivity values complied with the standards as they were below 7000 µS/cm. Finally, the TDS values were all below 5000 mg/L. It is evident that the soaping discharges are of average quality, and it is preferable to treat them before their release into sewerage system managed by ONAS.

Consequently, as shown in Fig. 3, wastewater quality parameters varied significantly across the denim finishing stages. The stone-washing stage exhibited the highest pollution load, with COD values reaching approximately 4500 mg/L, which is more than four times the regulatory limit (1000 mg/L). Similarly, TDS values increased to nearly 4800 mg/L during the neutralization stage, approaching the discharge limit of 5000 mg/L. Electrical conductivity also peaked during the dyeing and neutralization processes, exceeding 8000 µS/cm, which is above the standard limit of 7000 µS/cm. In contrast, the preparation and neutralization stages showed relatively lower TSS values (< 100 mg/L) compared with the stone-washing stage, where TSS exceeded 450 mg/L, surpassing the regulatory threshold of 400 mg/L. The pH remained mostly within the acceptable range (6.5–9), except during the neutralization stage, where values decreased to approximately 5–6, indicating the presence of acidic residues.

In this section of the study, the quality parameters varied according to the type of effluent analyzed throughout the monitoring period. Most effluents did not comply with Tunisian standards and therefore require purification treatments. In contrast, effluents from the dyeing preparation stage exhibited good quality and could either be reused in subsequent processes or discharged without treatment. In the following section, we will evaluate the potential reuse of denim effluents by calculating their Water Quality Index.

Evaluation of the quality of rinse bath effluents

The quality of rinse bath effluents generated from dyeing, stone washing, bleaching, neutralization, and soaping processes was evaluated over a monitoring period. The comparison of the measurements of different quality assessment parameters of denim discharge processes before and after rinsing was presented in the following Fig. 4.

Monitoring the quality of rinse bath effluents from dyeing process

Two successive rinsing steps are performed after the dyeing process. Before draining, a sample of each effluent was collected to evaluate its quality. After the two rinsing stages, we observed a remarkable improvement in the quality of the effluent, as illustrated in Fig. 4. Indeed, the pH of the baths decreased slightly after rinsing while remaining basic. In addition, the measured concentration of suspended solids (TSS) was greatly reduced during rinsing, thereby improving the overall quality of the effluent. Moreover, the variation in COD values after rinsing was highly significant, showing a substantial reduction in organic load. This can be explained by the fact that the number of organic bonds present in the dye bath effluent is much higher than in the rinsing effluents. Furthermore, the rinsing effluents became visibly clearer compared to the dye bath, as confirmed by the reduced Pt–Co color unit measurements. Finally, the last two measured parameters, conductivity and TDS, showed a considerable decrease after rinsing, indicating the removal of residual salts and electrolytes.

Monitoring the quality of rinse bath effluents from stone washing process

Stone washing is followed by two successive rinses, each lasting approximately two minutes. Prior to drainage, an effluent sample is collected to assess its quality. After the two rinsing steps, the quality of the rinse effluents is found to improve remarkably, as shown in Fig. 4. The pH remains nearly unchanged, with a slightly basic average value of 7.5. Moreover, TSS decreases significantly during rinsing compared to that measured in the stone washing bath effluent. Indeed, TSS value can reach 1290 mg/L, which exceeds the Tunisian regulatory limit of 400 mg/L, but after two rinses it decreases to 300 mg/L. It is noteworthy that a reduction in TSS concentration reflects an improvement in water quality. Furthermore, COD values drop considerably after the two rinses, clearly indicating a reduction in the organic matter content of the effluents. The color of the rinse effluents also becomes lighter, as observed both visually and through measurement on the platinum cobalt (Pt–Co) scale. Finally, the analysis of conductivity and TDS shows that their values remain nearly unchanged after rinsing.

Monitoring the quality of rinse bath effluents from bleaching process

Following the bleaching process, two successive rinsing steps, each lasting approximately two minutes, are carried out. Before draining each operation, a sample of the effluent is collected to assess its quality. By analyzing the different parameters of the collected samples in Fig. 4, it can be observed that the quality of the rinsing effluents improves significantly from one rinse to the next. Indeed, the pH of the rinsing baths remains alkaline even after rinsing, with an average value of 8, which complies with Tunisian standards. In addition, TSS values decreases remarkably. For sample 4 (S4), the TSS value was 300 mg/L, but after the two rinsing steps, this value decreased tenfold to 35 mg/L. Moreover, COD of the baths decreases considerably after rinsing. In fact, COD of the bleaching bath is difficult to measure initially because this effluent contains a high chloride concentration that interferes with the measurement. However, after rinsing, the COD becomes easier to determine, indicating that the chloride concentration in the water was significantly reduced. Similarly, the platinum-cobalt color unit decreases after rinsing, and the color of the effluents becomes lighter. Finally, the last two quality assessment parameters conductivity and TDS depend directly on the sodium hypochlorite concentration. A higher concentration leads to higher measurements, and vice versa. Since rinsing reduces concentration, these measurements also decrease accordingly. These findings are consistent with previous studies highlighting the effect of washing and rinsing on reducing pollutant loads in denim bleaching effluents[30].

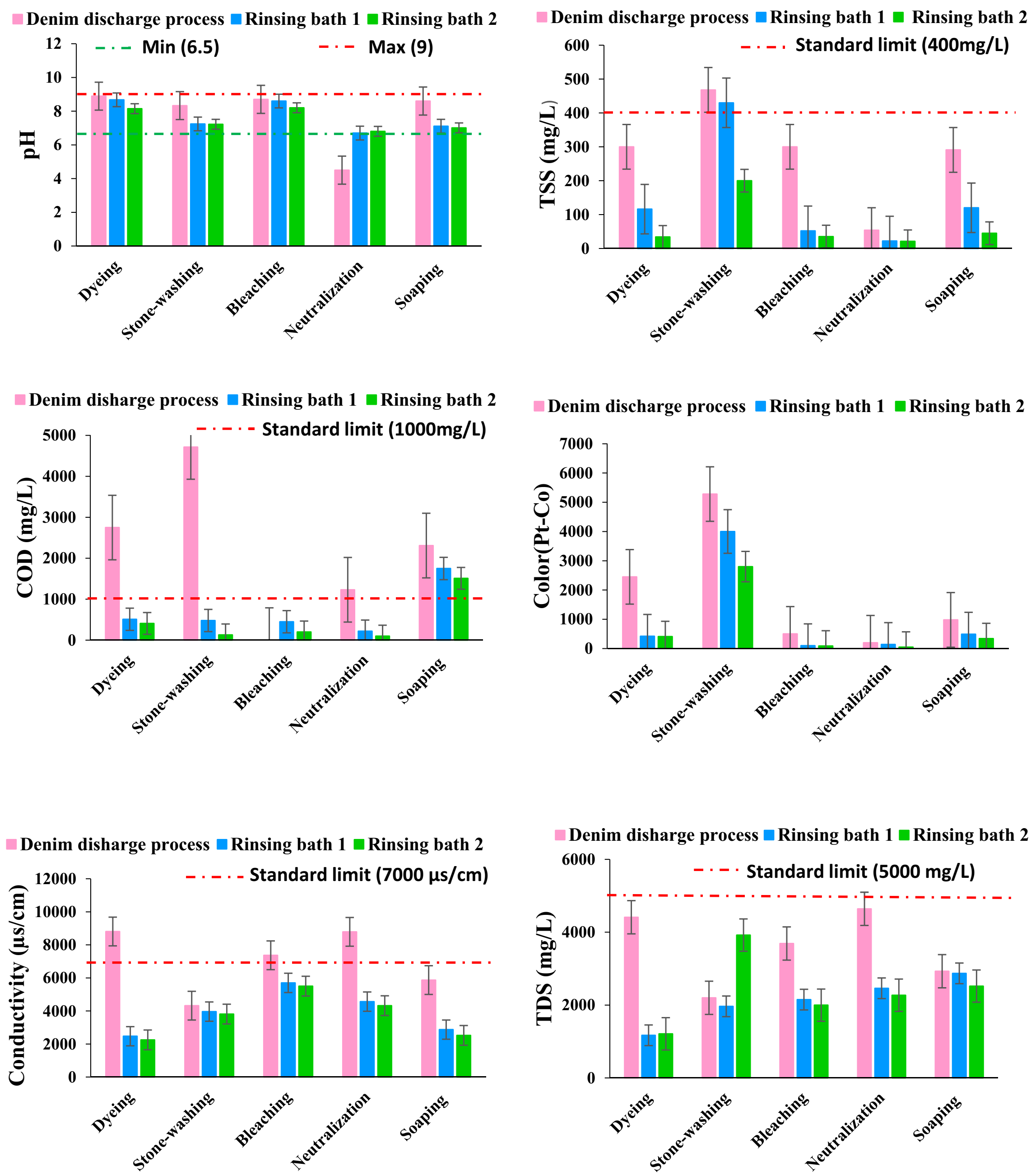

Fig. 4. Comparison of wastewater quality parameters of the denim finishing process before rinsing (denim discharge process) and after two rinsing steps (Rinsing bath 1 and Rinsing bath 2). The evaluated parameters include pH, TSS, COD, color (Pt–Co), conductivity and TDS across the main processing stages (dyeing, stone-washing, bleaching, neutralization, and soaping). Bars represent mean values and error bars indicate standard deviation. The dashed lines represent the regulatory discharge limits for each parameter (pH: 6.5–9; TSS: 400 mg/L; COD: 1000 mg/L; conductivity: 7000 µS/cm; and TDS: 5000 mg/L).

Monitoring the quality of rinse bath effluents from neutralization process

The neutralization process is followed by two successive rinsing steps, each lasting approximately two minutes. Before each discharge, a wastewater sample was collected to evaluate its quality. After the two rinsing steps performed on the treated articles, it was observed that the quality of the rinsing effluents improved significantly, as illustrated in Fig. 4. In fact, the pH increased progressively from one rinsing to another. The wastewater of the neutralization bath was acidic, with an average pH of 4, while the rinsing effluents became neutral. Additionally, a notable reduction in TSS was observed, even though the baseline TSS levels were already low before rinsing. Likewise, COD values decreased considerably after rinsing, confirming that the amount of organic matter was significantly reduced, thus improving water quality. The color unit also decreased after rinsing, and the rinsing effluents became visually clearer compared with those of the neutralization bath. Finally, conductivity and TDS dropped remarkably during the rinsing process, in line with previous findings on the efficiency of post-bleaching rinsing in improving effluent quality.

Monitoring the quality of rinse bath effluents from soaping process
Following the soaping process, two successive rinses of approximately two minutes each are carried out. Just before the drainage of each operation, an effluent sample is collected to assess its quality. After the two rinsing steps, the quality of the effluents is found to improve, as showed in Fig. 4. The pH remains stable between 7 and 8, even after rinsing, which falls within acceptable limits for textile effluents. Furthermore, TSS concentration decreases with rinsing, although it should be noted that TSS values are already low prior to rinsing. In addition, COD values comply with Tunisian standards, as they remain below 1000 mg/L, and this parameter decreases significantly after the two rinses. Similarly, the color unit of the effluents, measured on the platinum cobalt scale, is observed to decrease after rinsing. Finally, the conductivity and TDS values do not vary considerably because of rinsing, since the measured values remain of the same order of magnitude throughout the monitoring period.

Consequently, as shown in Fig. 4, the results indicate that pollutant concentrations are significantly higher in the raw discharge compared to the rinsing baths. The stone-washing stage exhibited the highest contamination levels, with COD reaching approximately 4700 mg/L, which is nearly 4.7 times higher than the regulatory limit (1000 mg/L). Similarly, color intensity exceeded 5000 Pt–Co, while TSS values approached 450 mg/L, slightly surpassing the permissible limit of 400 mg/L. Electrical conductivity also exceeded the recommended limit of 7000 µS/cm during dyeing and neutralization stages. After the first rinsing bath, a substantial reduction in pollutant concentrations was observed, with COD decreasing to approximately 400–600 mg/L depending on the stage. A further decrease was observed after the second rinsing bath, where COD and TSS values were generally below regulatory limits. In addition, pH values remained mostly within the acceptable range (6.5–9), except during the neutralization stage where lower values were recorded before rinsing. Overall, these results highlight the effectiveness of the rinsing steps in significantly reducing pollutant loads and improving the quality of wastewater generated during denim finishing.

Assessment of Water Quality Index in different treatment stages before and after rinsing

The Water Quality Index (WQI) results illustrated in Fig. 5 reveal pronounced process- and stage-dependent variations in wastewater quality across the denim finishing sequence, both before and after rinsing. Among the investigated stages, preparation for dyeing stands out as the least polluting stream, exhibiting the lowest WQI value (30.84), which corresponds to good water quality and minimal pollution loads, making it the most suitable candidate for direct reuse or discharge with minimal treatment. In contrast, dyeing effluents showed a substantial improvement after rinsing, with WQI values decreasing from 116.61 before rinsing (unsuitable category) to 65.72 after rinsing bath 1 (poor category) and further to 33.66 after rinsing bath 2 (good category), demonstrating the effectiveness of rinsing in reducing contaminant loads. However, other finishing stages generated considerably higher WQI values. The stone-washing, bleaching and soaping processes consistently

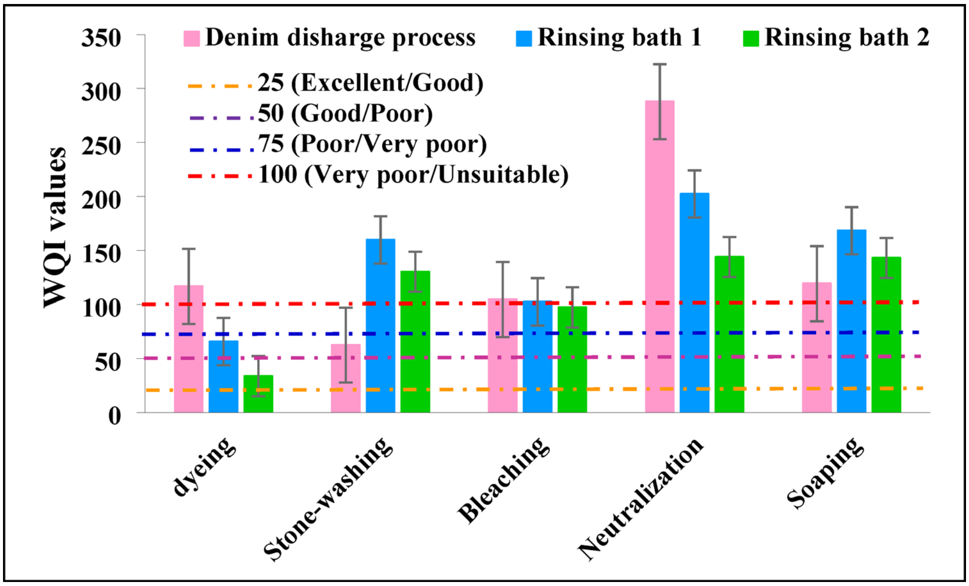

Fig. 5. Comparison of the Water Quality Index (WQI) values of wastewater generated during the denim finishing process before rinsing (denim discharge process) and after two rinsing stages (Rinsing bath 1 and Rinsing bath 2). The analysis covers the main processing steps: dyeing, stone-washing, bleaching, neutralization, and soaping. Bars represent mean values and error bars indicate standard deviation. The dashed lines indicate WQI classification thresholds: excellent (0–25), good (26–50), poor (51–75), very poor (76–100), and unsuitable for industrial reuse (> 100). WQI for the bleaching stage was calculated without COD due to chloride interference and is therefore based on a reduced parameter set.

generate moderate to high WQI values, frequently falling within poor to unsuitable quality classes even after the second rinsing step (reaching up to 130.13, 97.35 and 142.93, respectively). These elevated values are mainly associated with the release of suspended solids, surfactants, and residual organic compounds characteristic of these treatments. Among all stages, the neutralization process emerges unequivocally as the dominant pollution hotspot, with extremely high WQI values under all conditions. The WQI reached 287.8 before rinsing, and although it decreased to 202.2 and 143.78 after rinsing baths 1 and 2, respectively, the effluent remained within the unsuitable water quality category, indicating that rinsing alone is insufficient to ensure acceptable water quality.

It is important to emphasize that COD was excluded only for the bleaching stage due to analytical interference caused by high chloride concentrations, whereas it was retained in the WQI calculation for all other effluents. As a result, the sum of unit weights (ΣW_n) for bleaching is lower than unity, unlike the other stages where $\Sigma W_n = 1$. Therefore, the WQI values reported for bleaching correspond to a modified index based on four parameters and do not explicitly account for organic load. Because COD was excluded, this index is not strictly based on the same parameter set as those calculated for the other process stages, which limits direct quantitative comparability. While this approach ensures analytical reliability, it may lead to a slight underestimation of the overall pollution level. Such adaptations of WQI have been recognized in the literature as acceptable when certain parameters cannot be reliably quantified[22,26]. Accordingly, comparisons involving bleaching effluents should be interpreted with caution and supported by the analysis of individual physicochemical parameters. To further evaluate the robustness of the WQI results, a sensitivity analysis was performed. Given the very high weight assigned to pH in the original WQI formulation ($W = 0.974$), the WQI was recalculated after excluding pH and renormalizing the remaining weights to maintain $\Sigma W_i = 1$. As shown in Table 2, this resulted in a substantial redistribution of weights, with TSS and COD becoming the dominant parameters. Although the absolute WQI values were affected, the overall trends in effluent quality across the different process stages remained broadly consistent. This indicates that, despite the strong contribution of pH, the interpretation of water quality is not solely driven by a single parameter. Similar sensitivity analyses have been recommended in previous studies to evaluate the influence of weighting schemes on WQI outcomes[33,34]. However, the observed redistribution highlights the influence of weighting choices on WQI results and underscores the need for cautious interpretation of the index.

Overall, while rinsing baths play a crucial role in improving effluent quality, their effectiveness remains strongly process-dependent, underscoring the need for a process-specific wastewater management strategy that prioritizes reuse of low-impact streams such as preparation for dyeing and rinsed dyeing effluents, while enforcing advanced, targeted treatment for high-impact stages, particularly neutralization.

Assessment of the reuse potential of high-quality rinse effluent

A process-integrated cascading water reuse strategy was evaluated for denim processing, in which each wet-treatment stage (dyeing preparation, dyeing, stone washing, bleaching, neutralization, and soaping) is followed by two successive rinse baths. Monitoring the effluents revealed a progressive improvement in water quality from the first to the second rinse, resulting in final rinses of acceptable quality and demonstrating their suitability for in-plant reuse.

Under the scheme represented in Fig. 6, effluents from the first rinse bath of each operation are redirected to the main process of the subsequent cycle, while second rinse baths serve as first rinses in the next cycle. In the bleaching stage, first and second rinses are stored separately, tested for chloride content, and reused in the main bleach process and first rinse bath, respectively. The second rinse bath is then replenished with freshwater, achieving a substantial reduction in freshwater consumption, with an estimated value approaching two-thirds under the investigated process configuration. However, this value should be interpreted as a conceptual estimation based on process-level observations and rinse-water reuse potential, rather than as a result derived from a detailed plant-wide water balance. A similar approach is applied to soaping, with controlled detergent dosage, and these rinse waters can also be reused in stone washing due to the use of similar surfactants. Stone washing rinse baths can be repurposed by adjusting enzyme concentrations or pumice stone quantities, while neutralization rinse baths can be recycled by maintaining appropriate sodium metabisulfite dosing. Conversely, although dyeing rinse waters improve in quality and comply with regulatory discharge limits, their reuse is not feasible because trace dye residues alter garment shade consistency. Therefore, discharge to the ONAS sewer network remains the most appropriate option, simultaneously reducing purification costs. The proposed reuse strategy reduces freshwater intake by nearly two-thirds, which also translates into a proportional reduction in wastewater volume requiring external treatment. This reduction has implications for lowering treatment energy demand and sludge generation at downstream facilities.

Parameter	Original weight (W_i)	Weight without pH (Unnormalized)	Renormalized weight
pH	0.974	–	–
TSS	0.017	0.017	0.644
COD	0.007	0.007	0.265
TDS	0.0014	0.0014	0.053
Conductivity	0.001	0.001	0.038
ΣW_i	1	0.0264	1

Table 2. Influence of pH exclusion on WQI weighting: redistribution of parameter contributions following renormalization.

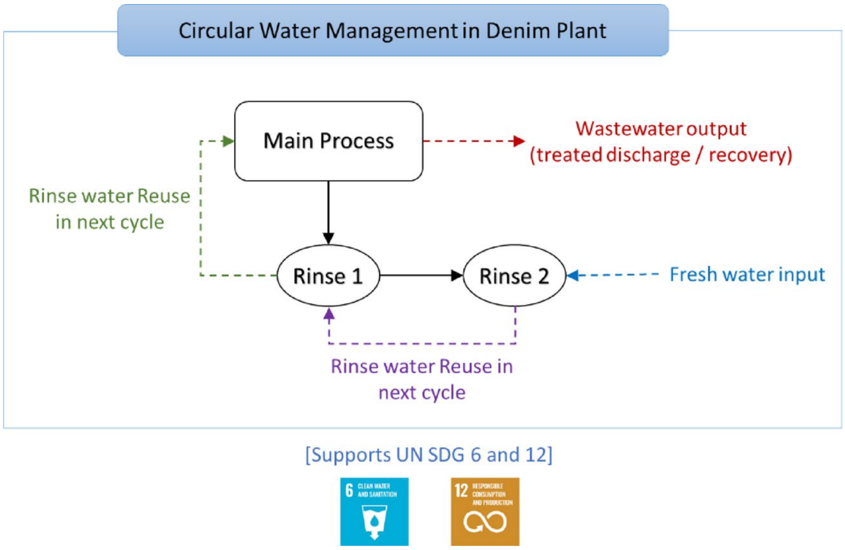

Fig. 6. Schematic representation of rinse water management and reuse strategy in the Denim plant.

This cascading reuse framework has the potential to minimize freshwater demand and effluent generation while supporting cleaner production practices. It should be noted, however, that the proposed strategy is based on process-level water quality assessment and operational compatibility and does not include direct experimental validation of textile quality parameters such as shade reproducibility, fabric properties or finishing performance. Furthermore, it should be explicitly noted that the proposed cascading reuse framework is intended as a qualitative decision-support tool and no pilot-scale implementation or repeated-cycle reuse trials were carried out within the scope of this study. Accordingly, the feasibility of long-term operation, potential accumulation effects and impacts on process stability and product quality remain to be validated under real industrial conditions. Nevertheless, it provides a promising approach for advancing sustainable water management in the textile sector, contributing to SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). Notably, the proposed cascading reuse strategy is not based solely on regulatory discharge limits but also considers the relative sensitivity of different process stages to water quality parameters. In this study, reuse pathways were identified based on WQI trends and general process requirements, rather than strict quantitative thresholds. As such, the framework is intended as a qualitative decision-support tool.

Future perspectives

The cascading reuse strategy proposed in this study is viewed as a process-oriented conceptual framework for identifying potential water reuse pathways within denim finishing operations, rather than a fully validated techno-economic implementation model. The present work focuses primarily on process-level water quality assessment and reuse feasibility based on WQI trends and process compatibility. Future research should therefore address long-term operational aspects, including techno-economic evaluation and the potential accumulation of dissolved salts during repeated reuse cycles. Parameters such as TDS and electrical conductivity may progressively increase due to salts originating from dyes and auxiliary chemicals. Assessing salt balance, accumulation dynamics, and mitigation strategies (controlled purge streams or targeted treatment) will be essential to support the sustainable large-scale implementation of cascading water reuse in denim finishing plants. In addition, future studies should include a detailed plant-wide water balance to quantitatively validate the freshwater savings associated with the proposed reuse strategy. Further research is also needed to evaluate the industrial applicability of the approach, particularly by investigating the impact of water reuse on textile quality attributes such as color consistency, fabric integrity and process performance. Future studies should include pilot-scale validation and repeated reuse cycle experiments to assess long-term performance, accumulation of dissolved substances and potential impacts on textile quality and operational stability.

Conclusion

This study provides a comprehensive evaluation of denim industry effluents, revealing significant variability in pollution load across processing stages and widespread non-compliance with national discharge standards. Effluents from stone washing, bleaching, neutralization, and soaping were identified as the most polluting, consistently exceeding regulatory limits for key parameters such as COD, color, and conductivity. In contrast, wastewater from the dyeing preparation stage was of sufficiently good quality to be considered for direct reuse or safe discharge.

The Water Quality Index (WQI) assessment before and after rinsing revealed clear process-related variations in effluent quality. Initial streams generally exhibited poor to unsuitable water quality, indicating their need for treatment or controlled management. However, rinsing significantly improved water quality across operations, with several rinse effluents reaching levels suitable for reuse. These findings demonstrate that process-specific reuse strategies, particularly for high-quality rinse waters, can contribute to reducing freshwater demand and lowering the volume of wastewater requiring treatment. This work introduces a process-specific and temporally resolved WQI-based monitoring strategy. This approach integrates effluent quality assessment with operational feasibility to guide circular water management in the denim industry. The findings provide an actionable framework for implementing sustainable reuse practices and optimizing resource efficiency. While the proposed WQI approach proved effective for comparative assessment of industrial effluents, future work could include a quantitative sensitivity analysis to further evaluate the influence of parameter weighting. In contrast to conventional studies that focus on aggregated wastewater streams, this work adopts a process-level perspective that enables targeted intervention and optimized reuse strategies. The integration of WQI with stage-specific analysis and cascading reuse design represents a novel and practical contribution to sustainable water management in the textile sector.

The proposed cascading reuse framework minimizes freshwater demand and effluent generation while maintaining product quality, supporting cleaner production practices and contributing to SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

Data availability

The datasets used and/or analyses during the current study available from the corresponding author on reasonable request.

Received: 14 February 2026; Accepted: 28 April 2026
Published online: 02 May 2026

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Acknowledgements
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/ 2025/01/34495).

Author contributions
Methodology, R.H. and N.M.; validation, R.H; investigation, R.H. and N.M.; writing—original draft preparation, R.H. and N.M.; writing—review and editing, R.H. and N.M.; supervision, R.H.; project administration, R.H.; funding acquisition, R.H.

Funding
This research was funded by Prince Sattam bin Abdulaziz University, project number PSAU/2025/01/34495.

Declarations

Competing interests
The authors declare no competing interests.

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