ECORFAN Journal Bolivia 12[22]1-12: e41222112
Article

Sustainable alternatives for water consumption in denim jeans washing: A systematic literature review

Alternativas sostenibles para el consumo de agua en el lavado de pantalones de mezclilla: Una revisión sistemática de literatura

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Classification:

Area: Engineering
Field: Engineering
Discipline: Chemical engineering
Subdiscipline: Water contamination

https://doi.org/10.35429/EJB.2025.12.22.4.1.12
History of the article:
Received: August 05, 2025
Accepted: October 30, 2025

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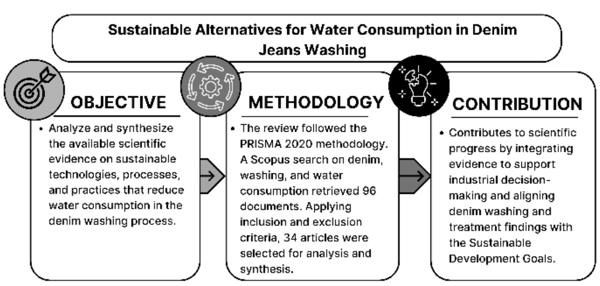
Abstract

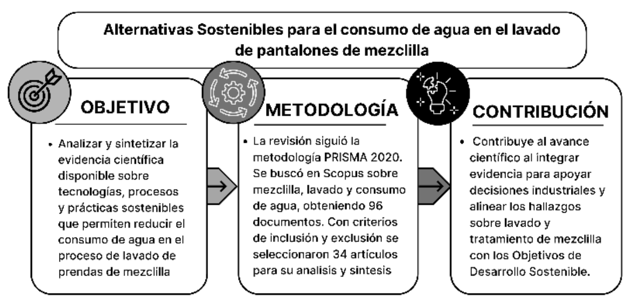
The denim industry is characterized by high consumption of water, energy, and chemicals, generating effluents with dyes, heavy metals, and toxic compounds that are difficult to treat. The objective of this systematic review was to analyze and synthesize scientific evidence on sustainable technologies, processes, and practices to reduce water consumption and optimize wastewater treatment in denim laundries. The study followed the PRISMA 2020 methodology, based on 34 articles retrieved from Scopus. The results highlight technologies such as ozone, laser, nebulization, and enzymes, as well as the reuse of natural materials such as peach pits and rice husk. These alternatives have shown substantial reductions in water, energy, and pollutants, although most remain at experimental stages and face technical and scalability limitations. It is concluded that the integration of clean technologies with efficient treatment systems is essential to reduce the denim industry's water footprint.



Denim, Water consumption, Sustainable processes

Resumen

La industria de la mezclilla presenta altos consumos de agua, energía y químicos, generando efluentes con colorantes, metales pesados y compuestos tóxicos de difícil tratamiento. El objetivo de esta revisión sistemática fue analizar y sintetizar la evidencia científica sobre tecnologías, procesos y prácticas sostenibles que reduzcan el consumo de agua y optimicen el tratamiento de efluentes en lavanderías de mezclilla. El estudio se desarrolló bajo la metodología PRISMA 2020, a partir de 34 artículos seleccionados en Scopus. Los resultados destacan tecnologías como ozono, láser, nebulización y enzimas, así como el reuso de materiales naturales como huesos de durazno y cascarilla de arroz. Estas alternativas muestran reducciones sustanciales en agua, energía y contaminantes, aunque la mayoría se encuentra en fase experimental y enfrenta limitaciones técnicas y de escalabilidad. Se concluye que la integración de tecnologías limpias con sistemas de tratamiento eficientes es indispensable para disminuir la huella hídrica de la industria.



Mezclilla, Consumo de agua, Procesos sostenibles

Area: Advocacy and attention to national problems

Citation: Araoz-Baltazar, Iván, Granados-Sánchez, Angelica, Martínez-Zárate, Israel and Del Angel-Medina, Oscar. [2025]. Sustainable alternatives for water consumption in denim jeans washing: A systematic literature review. ECORFAN Journal Bolivia 12[22]1-12: e41222112.

Introduction

The textile industry, particularly denim manufacturing, has been identified as one of the most resource-intensive sectors and one of the main contributors to water pollution worldwide. This sector consumes large volumes of water, chemicals, and energy, raising increasing concerns about its sustainability [Souza et al., 2016; Wahab & Hussain, 2020].

In particular, the garment finishing process, which includes industrial jeans washing, represents one of the most critical stages from an environmental perspective due to its high-water consumption, the chemical load of effluents, and the generation of solid waste and contaminant sludge [Atav et al., 2024; Nayak et al., 2022].

Traditional jeans washing requires between 30 and 70 liters of water, 150 g of chemicals, and 1 kWh of energy per garment [Ben Fraj & Jaouachi, 2021; Md. K. R. Khan & Jintun, 2021]. With an annual production of five billion pieces, global consumption is estimated at 350 million m^3 of water, in addition to indigo loss and other non-biodegradable substances that create a difficult-to-mitigate environmental footprint [Arenas et al., 2017; da Costa et al., 2021].

Added to this is the pressure from fashion trends, which impose aesthetic demands that become commercial standards and promote highly polluting processes [Ivedi & Cay, 2023; Md. K. R. Khan & Jintun, 2021]. Trends demanding specific textures and shades increase the use of water and chemicals, generate complex residues that are difficult to manage, and hinder the adoption of sustainable practices, despite growing regulations and environmental awareness [Luo et al., 2022; Nadeem et al., 2024].

Denim washing generates effluents containing recalcitrant dyes, heavy metals, and toxic compounds that alter pH, reduce dissolved oxygen, and harm aquatic life; some, such as aromatic amines, are carcinogenic or bioaccumulative [González-López et al., 2024; Rodríguez et al., 2013].

Many treatments only transform these contaminants into industrial sludge [Souza et al., 2016].

Furthermore, workers are exposed to hazardous chemicals and surrounding communities face water scarcity and deficient wastewater treatment [Vos, 2019; Wahab & Hussain, 2020]. Additionally, techniques such as pumice stone washing accelerate machinery wear, generate large volumes of sludge, and increase solid waste [Catarino et al., 2025; Ivedi & Cay, 2023].

Increasing public criticism, environmental regulations, and shifting consumer preferences have fostered scientific and industrial interest in developing sustainable solutions. However, these solutions face technical, economic, and operational challenges that hinder large-scale implementation, particularly in industrial contexts such as Tehuacán, Puebla, where denim production is a key regional economic activity. Despite this interest, the available evidence remains fragmented and lacks a rigorous synthesis to guide decision-making in the sector.

The objective of this systematic review is to analyze and synthesize the available scientific evidence on sustainable technologies, processes, and practices aimed at reducing water consumption in denim garment washing and its subsequent treatment, to identify technically, economically, and environmentally viable alternatives for potential implementation in industrial laundries.

The central hypothesis is that the integrated adoption of sustainable technologies and practices can significantly reduce the water and environmental footprint while maintaining the technical and economic viability of industrial laundries, thereby aligning with the United Nations Sustainable Development Goals [SDGs], particularly SDG 6 [Clean Water and Sanitation], SDG 12 [Responsible Consumption and Production], and SDG 13 [Climate Action], which promote sustainable water management, the reduction of industrial environmental impact, and the adoption of responsible production and consumption practices [ONU, 2015]. Sustainability constitutes a strategic and non-negotiable requirement for the long-term viability and competitiveness of the textile industry [Bastidas Paredes et al., 2025]

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The added value of this study lies in the fact that, unlike previous research focused on isolated cases or specific technologies, it provides a systematic and updated synthesis of scientific evidence on sustainable alternatives, offering a comparative and critical perspective that can guide decision-making in the denim industry.

This article is organized into four sections: the first describes the methodology used for systematic review; the second presents the main results; the third discusses the findings considering current challenges; and the fourth provides conclusions and recommendations for implementing sustainable processes in the denim industry.

Methodology

The development of this review followed the PRISMA 2020 methodology [Preferred Reporting Items for Systematic Reviews and Meta-Analyses], to ensure a rigorous, transparent, and reproducible process in the identification, selection, and analysis of the included studies [Page et al., 2021].

1.1. Search Strategy

An exhaustive search was carried out in the Scopus database, using a combination of key terms related to washing processes, denim, and water consumption. The search equation employed was as follows: *[technology OR washer OR machine OR "washing process" OR laundering OR laundry OR finishing] AND [denim OR jeans] AND ["water footprint" OR "water usage" OR "water consumption" OR "water reduction" OR "water treatment" OR wastewater OR sewage]*

This strategy initially retrieved a total of 96 documents, corresponding to different types of academic publications.

1.2. Inclusion Criteria

Documents were included if they met the following conditions: peer-reviewed articles on denim washing, finishing, treatment, or sustainability; studies on other fabrics with proposals applicable to denim; documents with accessible title and abstract; and research on wastewater treatment originating from denim laundries.

1.3. Exclusion Criteria

Documents were excluded if they met any of the following conditions: studies on denim fabric manufacturing or weaving without relation to garment finishing; research on wastewater treatment not originating from laundries; documents without an identified author or without an abstract; non–peer-reviewed publications; and outdated proposals or those lacking current contributions to sustainability in denim finishing.

1.4. Selection Process

From the initial total of 96 retrieved documents, the corresponding filters were applied according to the criteria above. As a result, 34 documents were selected for detailed analysis, including 28 scientific articles and 6 review articles. The filtering and selection process is shown in **Figure 1**.

Box 1

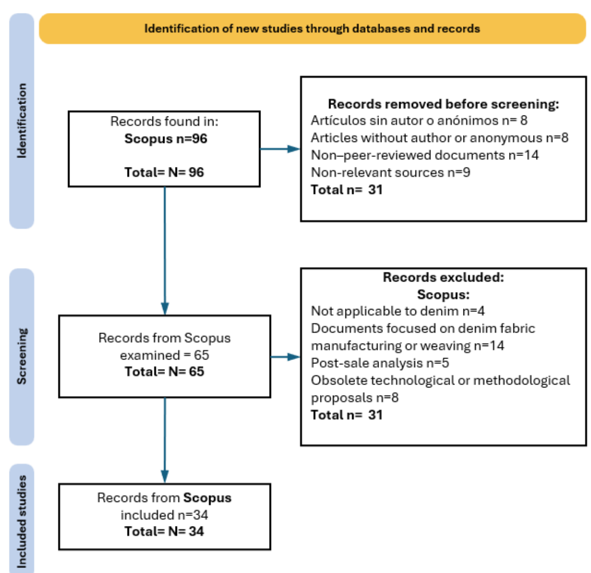

Figure 1
PRISMA 2020 Flow Diagram
Source: Own elaboration

Results

From the detailed analysis of the documents selected for this systematic review, it was possible to identify several research lines focused on sustainable alternatives for water consumption in the denim jeans washing process, which are described in the following subsections.

ISSN: 2410-4191.
RENIECYT: 1702902

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Box 2

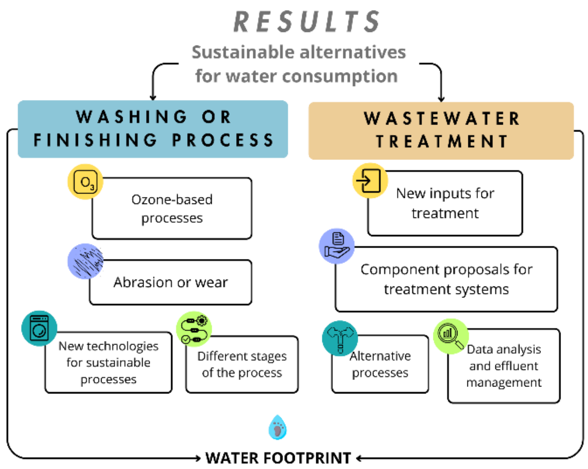

Figure 2

Conceptual map of the review results

Source: Own elaboration

Sustainable Optimization in Washing or Finishing Processes

One of the main objectives of denim garment finishing or washing is to provide a wide range of shades while ensuring consumer comfort. To achieve this, a large amount of chemicals, water, and energy is required, which makes conventional finishing processes—and the textile industry in general—one of the most polluting. [Arenas et al., 2017; Ben Fraj & Jaouachi, 2021; Chowdhury et al., 2020]. In this context and considering the sustainability approach that has been globally adopted by the industry in recent years, the denim sector has been compelled to research and implement modern washing and treatment techniques [Uysaler et al., 2025].

These efforts primarily aim to reduce water consumption, minimize environmental pollution, and decrease the generation of chemical waste and wastewater. Moreover, the intensive use of heavy chemicals in dyeing and finishing processes not only impacts the environment but also poses risks to workers' health.

All these factors reinforce the urgency for the textile industry to transition toward greener processes, clean technologies, and economically sustainable solutions [Arenas et al., 2017; Atav et al., 2024; Eroğlu, 2023].

1.4.1. Ozone-Based Processes

Ozone [O_3] is a gas naturally present in the atmosphere, generated through photochemical reactions induced by the sun's ultraviolet [UV] radiation. However, it can also be artificially produced through methods such as corona discharge, which forms the basis for the operation of ozone-generating machines in closed chambers [Atav et al., 2024; Ben Fraj & Jaouachi, 2021]. Ozone's oxidizing properties make it an efficient, consistent, and eco-friendly alternative to traditional denim bleaching methods. Among its most relevant advantages are its ability to avoid the formation of organochlorine residues, the drastic reduction in water consumption, and its natural reconversion into oxygen after the reaction. This prevents the formation of toxic by-products and reinforces their profile as an environmentally friendly technology [Nadeem et al., 2024]. **Table 1** presents the articles that investigated this technique and their respective proposals, as well as the benefits reported.

Box 3

Table 1

Proposals for ozone processes and benefits

Author	Author's proposal	Key Benefit
[Atav et al., 2024]	Ozone as a sustainable bleaching technology	Water, energy and chemical reduction; less polluting; greater fabric strength; lower cost per garment and lower carbon footprint.
[Ben Fraj & Jaouachi, 2021]	Ozone treatment as a substitute alternative for abrasives	Reduction of water and chemicals; better whiteness without toxic products; control over shrinkage, resistance and bagging; less environmental impact and energy consumption; avoids hazardous waste.
[Hu et al., 2021]	Optimization of ozone washing using the orthogonal method	Control of the bleaching effect; simplification of the operational process; Greater reproducibility of results; Process efficiency
[Nadeem et al., 2024]	Gaseous ozone with fine water aerosolization.	Substitution of toxic bleaches; lower consumption of water, chemicals and sludge generation; improvement of mechanical and comfort properties; reduction in BOD and COD of effluents; control and reproducibility; mass transfer efficiency.
[Nayak et al., 2022]	Combining digital laser and ozone technologies with data from two Vietnamese companies.	Water, energy and chemical savings; water-free and effluent-free processes; precise and creative finishing effects; reduction of environmental pollution. lower operating costs; circular economy.
[Ben Hmida & Ladhari, 2016]	Evaluation of ozone concentration, and its effects on physical and chemical properties of the tissue.	Reduction of hot water and chemicals; zero hazardous waste; Higher ozone efficiency in controlled wet environment; Less mechanical damage.

ISSN: 2410-4191.
RENIECYT: 1702902

Despite its multiple advantages, the ozonation process in denim garments presents technical and operational limitations that must be carefully considered. One of the main concerns is the loss of mechanical strength in fabrics, particularly when treatment times or concentrations are exceeded, since ozone can break hydrogen bonds in cellulose and weaken the fiber structure [Atav et al., 2024; Ben Fraj & Jaouachi, 2021].

Another important limitation is the saturation of ozone gas within the treatment chamber, which can reduce its effectiveness in prolonged or poorly ventilated processes [Nadeem et al., 2024]. In addition, the process is highly sensitive to operating conditions, such as humidity [excessive water reduces effective contact between ozone and fabric], medium pH, and temperature, which affect the solubility and lifespan of the gas [Atav et al., 2024; Hu et al., 2021]. It has also been reported that some synthetic materials, such as PET, exhibit lower reactivity to ozone due to their compact structure, requiring specific parameters for each fiber type [Nadeem et al., 2024]. Finally, although not always explicitly mentioned, the initial investment in specialized machinery and the need for trained technical personnel may represent a barrier to the adoption of this technology, particularly in developing countries [Nayak et al., 2022].

1.4.2. Alternatives for Wear or Abrasion

One of the most valued finishes by both designers and customers is the *stone wash*, whose objective is to create a worn or aged effect in denim garments.

This effect is achieved through abrasion or mechanical friction, produced by the rubbing of pumice stones against the garment inside the washing drum [Arenas et al., 2017; Ivedi & Cay, 2023].

As an alternative, the use of cellulase enzymes has been proposed, which can achieve a similar or even superior finish without relying on mechanical abrasion [Kakkar & Wadhwa, 2022]. However, in real industrial environments, it is common to combine both methods to achieve the desired levels of wear and visual contrast.

This process has several disadvantages, including the difficulty of removing stones from garments at the end of washing, textile fiber damage, reduced fabric strength, the appearance of tears, obstruction of machine pipelines due to stone fragmentation, potential damage to machinery, and high-water consumption [Arenas et al., 2017; Ivedi & Cay, 2023; Kakkar & Wadhwa, 2022].

Table 2 presents the three articles that addressed studies with this approach, listing the authors' proposals, the identified benefits and limitations, as well as the stage of implementation in which they are currently positioned.

Box 4

Table 2

Proposals for ozone processes and benefits

[Ivedi & Cay, 2023]	
Proposal	Evaluation of the use of peach peach and synthetic stones.
Proceeds	Reuse of natural and synthetic materials more than 100 timesReduction of up to 50% of water Lower CO_2 emission. 45% lower cost per unit Comparable results pumice stone
Limitations	Longer process time CO_2 emission up to 13–14% Lower washout visual effect
Phase	Experimental tests in a real industrial environment
[Kakkar & Wadhwa, 2022]	
Proposal	Use of **extremozymes** to replace chemical processes.
Proceeds	Eco-friendly and biodegradable processes; lower use of water, energy and chemicals; applicable in extreme conditions; quality improvement; Less pollutants in effluents.
Limitations	Expensive and difficult production under laboratory conditions; requires genetic engineering; some have redeposition or spots.
Phase	In the development and experimentation stage.
[Arenas et al., 2017]	
Proposal	Abrasive rice husk ash [RHA] spheres
Proceeds	Reduction of damage to garments and machinery; simultaneous adsorption of dye and solid waste; Zero effluent discharge processes.
Limitations	It was not validated in real effluent; no mechanical strength is reported; no aesthetic or physical effects are evaluated.
Phase	Experimental laboratory test.

Source: Own elaboration

ISSN: 2410-4191.
RENIECYT: 1702902

1.4.3. Alternatives in Different Stages of the Process

While ozone-based techniques and abrasion alternatives are the most widely studied within the scope of proposals applied to the washing process, the following individual studies aimed to develop, evaluate, and optimize sustainable processes for the washing, dyeing, or finishing of denim and cotton garments through alternative technologies such as laser treatment, automated systems, spraying methods, or enzymatic washing. These approaches seek to significantly reduce water, energy, and chemical consumption, as well as environmental impact, in comparison with conventional methods.

Table 3 presents five authors who proposed techniques, machines, chemicals, and methods oriented toward sustainably improving the efficiency of the washing process, along with the benefits and limitations identified.

Box 5

Table 3

Advantages and limitations of alternatives in different processes.

[Wahab & Hussain, 2020]	
Proposal	Adaptation of aerosol technology, using a mixture of pressurized air and minimal amount of water.
Proceeds	Water [75%] and energy [47%] savings; reduction of chemicals; color fastness and less rinsing.
Limitations	It requires redesign of machinery; only tested on socks; no aesthetic impact was evaluated.
[Chowdhury et al., 2020]	
Proposal	Substitution of sulfuric acid for acetic acid in the acid wash process, and use of sodium hyposulfite as a permanganate neutralizer instead of oxalic acid.
Proceeds	Use of safer substances; visual effects similar to the traditional method; simple and less corrosive processes.
Limitations	Slow bleaching; not validated on a large scale; requires testing on other denim blends.
[Hasan et al., 2024]	
Proposal	Misting where fine mist is used to apply finishing products.
Proceeds	Water [90.01%] and energy saving; high reproducibility and stability of the fabric; evaluation with EIM software.
Limitations	High chemical impact [EIM=85] due to the use of permanganate; safer alternatives were not evaluated; system depends on traditional chemicals.
[Nergi et al., 2023]	
Proposal	Process redesign by eliminating hypochlorite and permanganate, by organic bleach and laser
Proceeds	Lower water footprint [36%], lower gas use and permanganate elimination; Comparable visual quality.
Limitations	Higher electricity consumption [+46%]; it requires new products; terrestrial toxicity.
[Uysaler et al., 2025]	
Proposal	Optimization of the CO_2 laser washing process and 10 minutes of enzymatic washing
Proceeds	Process without hazardous chemicals; less energy and time; good visual and mechanical properties.
Limitations	Increases yellowness and reduces drag; still requires a wet stage; applied only on two types of denim.

Source: Own elaboration

1.5. Sustainable Optimization in Wastewater Treatment.

Once the desired processes requested by customers are applied to denim garments, the water used—mixed with chemicals, dyes that do not bind to the fiber during the dyeing process, and residues such as lint—is discharged as wastewater. The high variability of these processes results in effluents with elevated concentrations of pollutants and a highly diverse composition, including synthetic organic substances such as detergents, dissolved salts, and numerous suspended solids. [Ergan et al., 2025; Majouli et al., 2012]. These effluents generally exhibit high values of pH, biochemical oxygen demand [BOD], chemical oxygen demand [COD], turbidity, and other toxic chemical compounds [Souza et al., 2016].

The treatment and recycling of effluents produced by the textile industry, utilizing advanced technologies, equipment, and materials, represent a task of significant importance. In recent years, the search for more efficient and sustainable wastewater treatments has become an increasing challenge, driven by rising environmental awareness and stricter environmental protection regulations. [Augusto Moreira et al., 2025; Catarino et al., 2025; Ergan et al., 2025]

1.5.1. Proposals for New Inputs

Among the alternatives to optimize wastewater treatment generated by processes applied to denim garments, several proposals have focused on the use of specific inputs or chemical products, which have been analyzed in various studies for their potential to improve the purification process.

Table 4 presents three studies in which the authors proposed new inputs aimed at adaptation in wastewater treatment. In addition, a fourth article by Méndez-Hernández et al. [2022] is included, which, although it does not evaluate the benefits of the analyzed input, focuses on its toxicity—a contribution that is also highly relevant for decision-making in industrial and environmental contexts.

Box 6
Table 4
Proposals for inputs in effluent treatment systems

[da Costa et al., 2021]	
Proposal	Use of activated carbon from sugarcane bagasse to treat effluent.
Proceeds	High color removal [93%], low cost, effective with colorants.
Limitations	Does not meet COD standard, no affinity for other compounds and unadjusted pH.
Phase	Laboratory test with real effluent.
[Körlü et al., 2015]	
Proposal	Reuse of pumice stone as an adsorbent.
Proceeds	Reduction of COD/BOD, good performance with color, low cost and reuse of waste.
Limitations	The process is dependent on the initial dye concentration, does not eliminate all contaminants, and has not been evaluated for regeneration capability.
Phase	Test in industrial plant with real effluent.
[Augusto Moreira et al., 2025]	
Proposal	Synthesis of mesoporous silica with rice ash to remove methylene blue [MB] and contaminants.
Proceeds	High efficiency [~75%], good MB adsorption, high specific surface area and sustainable method.
Limitations	Efficiency only at pH 12, no regeneration study, not integrated with other technologies.
Phase	Laboratory test with real industrial effluent.
[Méndez-Hernández et al., 2022]	
Proposal	UASB anaerobic treatment of wastewater with high toxicity using Biolite BSN.
Proceeds	50% reduction in toxicity and 77% reduction in COD, identifies the toxic agent and possible methane recovery.
Limitations	Only simulated effluent was used, and toxicity remains high.
Phase	Laboratory test with simulated water.

Source: Own elaboration

1.5.2. Alternative Wastewater Treatment Processes

Given the limitations of conventional treatments, such as high sludge generation, excessive use of reagents, or reduced efficiency against certain pollutants, research on alternative processes has been promoted. These new methodologies—which include advanced biological treatments, chemical oxidations, hydrodynamic cavitation, and electrochemical technologies—seek not only to improve efficiency in pollutant removal but also to reduce energy consumption and facilitate the reuse of treated water [Solís et al., 2013; Zapata et al., 2021].

Table 5 lists five authors who proposed new techniques and methodologies for wastewater treatment. The exploration of these alternatives represents a significant step toward a more circular and responsible model in water resource management within the textile industry.

Box 7
Table 5
Proposals for new techniques and methodologies

[Solís et al., 2013]	
Proposal	Sedimentation as a physical pretreatment to reduce solids, color and COD in denim effluents.
Proceeds	Up to 70% COD reduction, visible colour reduction, economical technique and allows water to be reused.
Limitations	Ineffective for dyeing, does not remove organic load or phytotoxicity, requires additional treatment.
Phase	Try it in real laundries in Tepetitla, Tlaxcala.
[González-López et al., 2024]	
Proposal	Use of native microorganisms for biological treatment without external activated sludge.
Proceeds	90% reduction in COD and color, easy start-up, local and sustainable alternative, low health risk.
Limitations	Slower color removal and no evaluation of fungus or long-term stability.
Phase	Laboratory test with real effluent.
[Butrón et al., 2007]	
Proposal	Indigo electrochemical incineration with FM01-LC cell and BDD electrodes.
Proceeds	100% removal and mineralization, energy efficient and no chlorine or additional reagents.
Limitations	Only in the laboratory, without analysis of by-products and mechanism not described.
Phase	Try synthetic solution.
[Yigit et al., 2009]	
Proposal	Bioreactor with membranes [MBR] for continuous treatment of textile water.
Proceeds	High removal of contaminants [>95%], process stability, possibility of reuse.
Limitations	It does not remove TDS, requires nanofiltration, temporary loss of efficiency, and is not validated on an industrial scale.
Phase	Pilot test in denim plant.
[Zapata et al., 2021]	
Proposal	Hydrodynamic cavitation to remove physicochemical and microbiological contaminants.
Proceeds	Reduction of pH, TSS, BOD5, COD, fats, oils and E. coli, low energy consumption, complies with regulations.
Limitations	No temperature control recommends combining with other technologies to improve results.
Phase	Try real laundry effluent.

Source: Own elaboration

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1.5.3. Proposals for Components in Textile Effluent Treatment Systems

The treatment of textile effluents represents a significant environmental challenge. To address these issues, several studies have focused on the design and optimization of components that integrate treatment systems, such as filtering materials, electrodes, modular reactors, and biological media. The proper selection and arrangement of these components directly influence the efficiency of the physical, chemical, or biological processes applied [Majouli et al., 2012].

For electrochemical treatments, for example, the choice of electrode type and hydrodynamic conditions are critical factors to ensure high pollutant removal without generating secondary waste [Rodríguez et al., 2013]. On the other hand, in biological systems, the type of support material in biofilters can determine adsorption capacity and the development of useful microorganisms for the degradation process [Moesriati & Wardani, 2019]

The technological component proposals summarized in **Table 6** aim to enhance overall treatment efficiency, facilitate scalability and adaptability, and advance toward more sustainable solutions for the textile industry.

Box 8

Table 6

Technological components for effluent treatment systems

[Majouli et al., 2012]	
Proposal	Ceramic microfiltration membrane with Moroccan perlite to treat textile effluents.
Proceeds	It removes turbidity, reduces COD [54–57%] and Kjeldahl Total Nitrogen [TKN] [56%], completely discolors and reduces the cost of the product.
Limitations	It does not remove soluble contaminants, no shelf life and lower efficiency than commercial membranes were evaluated.
Phase	Laboratory test with real laundry effluent.
[Moesriati & Wardani, 2019]	
Proposal	Anaerobic biofilters with three filter media for denim wastewater.
Proceeds	Reduction of Chemical Oxygen Demand [COD] [91.67%], Total Suspended Solids [TSS] [88.89%] and color [82.66%], passive and economical system and better performance with bioballs.
Limitations	Only first days of operation and no long-term evaluation or compliance with standards.
Phase	Pilot test [24 L; HRT of 8 h].
[Rodríguez et al., 2013]	
Proposal	DSA electrodes in FM01-LC reactor for degrading indigo carmine in chloride medium.
Proceeds	100% bleaching and mineralization, lower energy consumption than Boron-Doped Diamond [BDD], and potential for industrial scale-up.
Limitations	Zero absorbance and loss of efficiency at high densities were not achieved.
Phase	Test with model solution and real effluent.

1.6. Water Footprint

The Water Footprint [WF] is an indicator that quantifies the total volume of freshwater consumed or polluted throughout the life cycle of a product, and it is distinguished into three components: blue water [surface or groundwater not returned], green water [rainwater stored in the soil], and gray water [the amount of water required to dilute pollutants] [Hoekstra & Mekonnen, 2012].

This measure also enables the evaluation of real and comparable environmental impacts, serving as a useful tool for management and environmental labeling when properly contextualized [Forin et al., 2020]. In the specific case of textile products such as jeans, **Table 7** lists two documents that analyzed the full life cycle water footprint of a pair of cotton jeans.

Box 9

Table 7

Water footprint analysis documents

Criteria / Author	[Luo et al., 2022]	[Vos, 2019]
Type of water footprint	Scarce water, eutrophication Ecotoxicity	Blue and green water
Methodology	Modular, process-based assessment for the entire lifecycle [CF + WF]	Spatially explicit water footprint [hybrid approach between LCA and WFA]
Life cycle stages	Complete: from cultivation to end-of-life [use and disposal]	From cultivation to domestic use [does not include final disposal]
Results	13.74 m³ H_2O eq [scarce water] 1.67×10^{-2} kg PO_4^{3-} eq [eutrophication] 112.41 m³ H_2O eq [ecotoxicity]	2,701 L of blue water and 2,031 L of green water per garment
Contributions in water consumption	Textile finish, cotton cultivation and consumer domestic use	Cotton cultivation [64%] and consumer washing [32%]
Sustainability	Demonstrates the effectiveness of the modular method for identifying critical processes, assessing sensitivity, and usage scenarios	Locate geographic hot spots in the supply chain, useful for corporate decisions

Source: Own elaboration

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https://doi.org/10.35429/EJB.2025.12.22.4.1.12

Conclusions

The results of this systematic review reveal that, although there have been significant advances in the development of sustainable alternatives to reduce water consumption in the denim washing process, most of the identified proposals are still at the experimental or pilot stage. Of the 34 studies analyzed, only a small number reported implementation at an industrial scale under real operating conditions, which limits their practical applicability across diverse production contexts.

Furthermore, a concentration of research was observed in specific technologies such as ozone, laser, or nebulization, which have demonstrated substantial reductions in water, energy, and chemical consumption. However, these technologies present technical limitations, high adoption costs, and reliance on specialized equipment, which hinder their widespread application, particularly in small- and medium-sized manufacturing enterprises.

A noted limitation is the limited research available on comprehensive wastewater treatment systems suitable for industrial laundries. Most studies have focused on individual inputs or components, without considering the comprehensive optimization of treatment plants that integrate energy efficiency, minimal sludge generation, and the possibility of water reuse. This fragmentation restricts progress toward scalable and replicable solutions.

Another identification is the lack of differentiated studies on the specific water footprint for each type of washing and finishing. The absence of detailed metrics on the water impact of different colors or treatments prevents precise comparisons between technologies and limits the design of public policies that promote rational water use. Having this information would allow the establishment of differentiated regulations that more effectively control water consumption according to the type of process and its level of impact.

In this context, it is concluded that greater investment is still needed in research, technological development, and systemic evaluation of sustainable solutions that integrate both the washing process and subsequent effluent treatment.

These actions are essential to advance toward the fulfillment of the Sustainable Development Goals, particularly those related to clean water, responsible production, and climate action.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

Author contribution

Araoz-Baltazar, Iván: Project idea, literature review, supervision, final validation, and conclusions.

Del Angel-Medina, Oscar: Literature review, methodological development, and conclusions.

Granados-Sánchez, Angelica: Data analysis, review of graphs, and conclusions.

Martínez-Zárate, Israel: Literature review, abstract, results, contributions, revisions, and conclusions.

SECIHTI areas

This project aligns with the SECIHTI areas of "Advocacy and attention to national problems" and "Development of strategic leading-edge technologies and open innovation for social transformation," as it addresses the urgent environmental and social challenges linked to wastewater generated in the denim industry, a key economic activity in Tehuacán, Puebla, through the exploration of innovative, sustainable treatment alternatives that can be scaled and transferred to similar contexts

Availability of data and materials

The articles analyzed in this research are found in Scopus and Google Scholar databases.

Funding

This work was funded by the Tecnológico Nacional de México through the 2025 Call for Scientific Research, Technological Development, and Innovation Projects of the Federal and Decentralized Technological Institutes and Centers, under project code 23263.25-P.

Acknowledgements

Indicate if they were financed by any institution, University or company.

Abbreviations

BDD	Boron-Doped Diamond
CF	Carbon Footprint
BOD	Biochemical Oxygen Demand
BOD5	Biochemical Oxygen Demand at 5 days
COD	Chemical Oxygen Demand
DSA	Dimensionally Stable Anode
EIM	Environmental Impact Measurement
LCA	Life Cycle Assessment
MB	Methylene Blue
MBR	Membrane Bioreactor
O_3	Ozone
SDG	Sustainable Development Goals
UN	United Nations
PET	Polyethylene terephthalate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
UASB	Upflow Anaerobic Sludge Blanket
UV	Ultraviolet radiation
WF	Water Footprint
WFA	Water Footprint Assessment

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