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LIFE CYCLE ASSESSMENT OF WASTEWATER TREATMENT IN A TEXTILE DYEING FACILITY

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ABSTRACT

This study evaluates the environmental impact of wastewater treatment in a textile dyeing plant through a Life Cycle Assessment (LCA) following ISO 14040-44, comparing three scenarios: (1) standard biological treatment, (2) electrochemical treatment (EC), and (3) an optimized system with water recirculation and hydrogen recovery. The results demonstrate that Scenario 3 is the most sustainable, achieving a 70% reduction in freshwater consumption–dropping from 1,000 L to just 300 L per 100 kg of fabric. This optimized approach also reduces chemical inputs, such as NaCl and Na_2CO_3, by 70%. From an energy perspective, the recovery of green hydrogen as a by-product provides approximately 9.9 MJ of energy per 100 kg of fabric, contributing to a 35% decrease in operating costs. Economically, the transition to Scenario 3 results in a total saving of €3.50 per kg of fabric compared to the conventional system. By effectively mitigating pollutant loads and drastically lowering the water and carbon footprints, this study provides data-driven evidence for decision-makers to adopt electrochemical processes. Ultimately, the integration of resource recovery proves that the textile industry can achieve significant industrial-scale savings, estimated at €1,050 per day, while maintaining high environmental standards.

1. INTRODUCTION

The textile industry is a major contributor to global industrial wastewater pollution, accounting for approximately 20% of total discharges worldwide (Velazquez, J., 2024). Within this sector, cotton dyeing and finishing processes are particularly critical due to their high consumption of water and chemical auxiliaries, such as sodium chloride and sodium carbonate. These processes generate large volumes of saline effluents containing recalcitrant organic matter and non-biodegradable dyes, which significantly challenge conventional wastewater treatment facilities.

Azo dyes, which account for over 80% of synthetic dyes, pose severe risks to environmental and human health due to their high stability and toxicity. When discharged into water bodies, they obstruct light penetration, inhibiting photosynthesis and depleting oxygen levels in aquatic ecosystems. Most critically, the reductive cleavage of the azo bond releases aromatic amines, many of which are known carcinogens and mutagens linked to bladder cancer and skin sensitization. These compounds tend to bioaccumulate, creating long-term ecological damage and significant health hazards for textile workers and surrounding communities. Consequently, their removal from industrial wastewater is a vital environmental priority to prevent the degradation of global water resources (Alzain et al., 2023; Boya Gao et al., 2022).

Because these complex pollutants are not effectively removed by standard biological treatments—where high conductivity can further inhibit essential microbial activity—facilities often require energy-intensive tertiary processes to meet discharge standards. This technological gap frequently results in high operational expenditures related to chemical usage and sludge management. Consequently, addressing these environmental challenges requires the integration of advanced technologies, such as electrochemical treatments, to enhance the degradation of persistent organic loads and facilitate safer discharge or water reuse (Ocampo, S., 2019; Cortazar Martínez, A., et al., 2025).

Given these characteristics, the textile finishing industry is considered a promising candidate for electrochemical treatments, which could enhance the degradation of recalcitrant organic matter while simultaneously enabling hydrogen (H_2) production—an approach especially relevant since the sector generates effluents with high conductivity

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and complex organic loads (Cuesta-Mota, D. et al., 2024a). Furthermore, it ranks among the top five industries in the European Union in terms of water use (79.6 m³ tCO_2/t of fabric produced) and CO_2 emissions (15–35 eq/t of fabric produced) (European Topic Centre on Waste and Materials in a Green Economy, 2019; Roth, J. et al., 2023). At the process level, textile dyeing itself is highly intensive in water and energy: consumption values range from 10 to 300 L of water per kg of fabric (Samanta, k. et al. 2019), with finishing-dyeing operations reaching 60–314 L/kg and peaks of up to 645 L/kg (Ketelsen, M.et al., 2020). For cotton dyeing, conventional procedures average around 120 L/kg (Reza-Ul-Hoque, M., 2023). Beyond water use, recent studies have quantified the carbon footprint of reactive dyeing, reporting emissions of 5–7 kg CO_2-eq per kg of fabric depending on the recipe and process (Zhu et al., 2024). Digital optimization of dyeing operations has been shown to significantly reduce both greenhouse gas emissions and water consumption (Kim et al., 2024). Pollutant loads remain a pressing concern, as dyeing effluents often exhibit high salinity and persistent dye content, posing serious environmental challenges (Hoque et al., 2024). These very characteristics, as discussed, make textile effluents particularly suitable for the application of electrochemical treatments. In particular, for the Catalonia region where this study is focused, the water consumption, the reduction of the carbon footprint and the emission of less pollutants are considered as priorities that the textile industry shall assess.

In this region, the environmental urgency is heightened by severe hydric stress due to the fact that this zone currently experiencing the worst drought in its recent history, with reservoir levels dropping below 16% of total capacity (Velazquez, J. , 2024).

Consequently, strict restrictions have been imposed on water usage, and regional authorities have set ambitious targets, such as reusing up to 70% of treated water by 2040 (Oria, I., 2024). Implementing advanced water recovery strategies in industrial sectors is therefore critical to mitigating water scarcity and adapting to long-term climate challenges (Palermo, F., 2024).

The shift towards sustainability in the textile sector is also driven by the need to reduce greenhouse gas (GHG) emissions. Hydrogen has emerged as a promising alternative to fossil fuels, given its high energy density and its only combustion by-product being water vapor. The integration of hydrogen production into textile wastewater treatment could simultaneously address water reuse and renewable energy generation goals (TEXTIMCA, 2025 and Zeng, K., & Zhang, D., 2010).

Electrochemical treatment processes have proven highly effective in removing dyes and complex organic pollutants from textile effluents while enabling the recovery of salts and alkalinity for reuse (Fabregas, 2021). Furthermore, electrochemical oxidation has shown energy consumption levels (approx. 3.5 kWh/m3) comparable to conventional textile wastewater treatment plants (Buscio et al., 2019). While several studies have explored these technologies for decontaminating synthetic organic dyes (Brillas & Martínez-Huitle, 2015; Sala & Gutiérrez-Bouzán, 2014), the focus has primarily been on anodic oxidation. In these systems, hydrogen is simultaneously generated at the cathode as a by-product, but it is generally extracted only for safety reasons. Consequently, very few studies have addressed the recovery of this hydrogen (Pathak et al., 2020; Cuesta-Mota et al., 2024a), despite its potential to substitute natural gas in industrial heat generation, thereby reducing fossil fuel dependency and carbon emissions (Ottosson, 2021).

To address this gap, our research group has designed and constructed a dual-compartment reactor separated by an ion exchange membrane. This configuration produces impurity-free hydrogen, similar to specialized alkaline electrolyzers (Cuesta-Mota et al., 2026). The experimental data obtained from this prototype, integrated with industrial data, has been used to generate the Life Cycle Inventory (LCI) for a Life Cycle Assessment (LCA). This allows for a comprehensive comparison of the environmental impact between this integrated water and hydrogen-recovery system and conventional biological treatments.

Life Cycle Assessment (LCA), in accordance with ISO 14040/14044 guidelines, offers a comprehensive framework to evaluate the environmental performance of such process innovations. By comparing scenarios with conventional and electrochemical treatments (with and without water reuse), it is possible to quantify resource savings, emission reductions, and the overall circularity potential of the proposed system. Scientific research into the textile sector and wastewater treatment has applied Life Cycle Assessment (LCA) to compare advanced technologies against conventional biological methods like Activated Sludge Processes (ASP). Key studies often focus on Advanced Oxidation Processes (AOPs), such as electrocoagulation and ozonation, highlighting that while these methods are efficient at removing persistent color and COD, their environmental burden is heavily influenced by electricity and chemical consumption (Bilinska et al., 2017; Muñoz et al., 2009).

This study applies life cycle assessment (LCA) to three process configurations for dyeing cotton fabrics, evaluating their environmental impact and resource recovery potential. The objective is to provide evidence-based information on the role of electrochemical treatment and hydrogen valorization in promoting circularity in the textile industry, including an economic estimate of the savings achieved through recovery and recirculation processes. The main novelty of the LCA performed in the current study is the evaluation of a circular system that simultaneously treats wastewater, recovers hydrogen (H2), and enables resources and water recirculation.

2. METHODOLOGY

Life Cycle Assessment (LCA) is a standardized methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle from the extraction of raw materials, manufacturing, and distribution, to use, end-of-life treatment, and disposal or recycling. The main goal of an LCA is to provide a comprehensive and quantitative understanding of how a product or process affects the environment, enabling the identification of opportunities for improvement and more sustainable decision-making. In this work, the LCA methodology following ISO 14040–44 has been applied to assess the environmental impacts and analyze the benefits associated with three different scenarios of the same dyeing production process, with the aim of providing a comprehensive quantitative view and determining their overall environmental performance.

An LCA typically follows the framework established by the ISO 14040 and ISO 14044 standards and consists of four main phases: (1) Goal and scope definition, where the purpose, system boundaries, and functional unit are defined; (2) Life cycle inventory (LCI), involving the collection and quantification of inputs (materials, energy) and outputs (emissions, waste); (3) Life cycle impact assessment (LCIA), in which the potential environmental impacts are evaluated; and (4) Interpretation, where the results are analyzed and conclusions are drawn to support recommendations.

The goal and scope of this study are defined in accordance with ISO 14040 and ISO 14044 standards. The main objective is to compare three different scenarios of the same dyeing production process, which, depending on the configuration, may include water recirculation and recovery of heat and hydrogen.

The intended application of the study is to support decision-making regarding resource efficiency and environmental performance improvements in water-stressed regions. The target audience includes researchers, industry stakeholders, and policymakers.

The system boundaries are defined as cradle-to-gate in order to provide a comprehensive assessment of the three scenarios, considering recovery options and potential environmental savings. The study includes all relevant processes from raw material extraction for chemicals and energy production up to the finished dyed and centrifuged cotton fabric and the associated wastewater treatment processes. Upstream processes such as cotton fiber cultivation and spinning, as well as downstream use and end-of-life phases, are excluded. These exclusions are justified based on cut-off criteria related to relevance to the comparative objective and expected negligible contribution to the differences between scenarios.

The functional unit is defined as 100 kg of conventionally dyed and finished cotton fabric under industrial conditions. The reference flow corresponds to the quantity of raw materials, energy, water, and auxiliary substances required to produce this amount of finished fabric with equivalent quality characteristics across all scenarios. This functional unit ensures comparability of environmental impacts between alternatives.

The impact assessment is performed using a recognized Life Cycle Impact Assessment (LCIA) methodology, and the selected impact categories are justified according to the objectives of the study and the ISO 14044 requirements. Given the geographic context characterized by strong water stress, the following impact categories are considered: water consumption, global warming potential (expressed as kg CO_2-eq/kg of fabric), pollutant loads (salinity and dye residues in effluents), and human health impacts related to exposure to toxic substances and degraded water quality. Global warming potential is used as the indicator for climate change to avoid duplication with carbon footprint metrics.

The system boundaries therefore include:

- Water and energy inputs for dyeing and finishing operations.
- Chemical auxiliaries (e.g., sodium chloride, sodium carbonate, reactive dyes).
- Direct emissions to water (saline effluents, residual dyes).
- Direct emissions to air (CO_2 and other greenhouse gases from energy use).
- Wastewater treatment processes, including biological and physicochemical stages.

Infrastructure and capital goods are excluded from the analysis, as their contribution is considered negligible within the comparative framework. Allocation procedures are not required unless multifunctionality arises in recovery stages, in which case allocation is performed based on physical relationships or system expansion, following ISO recommendations.

Primary industrial data are used for the core dyeing and centrifugation processes, complemented by secondary data from recognized databases for background processes. The reference year of the data and data quality indicators (technological, geographical, and temporal representativeness) are documented. An uncertainty analysis and data quality assessment are conducted to ensure robustness of the results.

Figure 1 illustrates the schematic layout of the three study scenarios and defines the system boundaries, with Scenario 1 representing the current conventional process. In this configuration, the dyeing stage includes the consumption of energy, natural gas, chemicals, cotton input, and water, corresponding to 1,000 liters of water per 100 kg of cotton. After dyeing, the fabric proceeds to the centrifugation stage. Approximately 30% of the water is discharged from the centrifugation process together with dye residues and sodium carbonate, among other components. Additionally, around 70% of the water is discharged directly from the dyeing process, containing residual dyes and chemical substances such as sodium carbonate. These two effluent streams are combined and undergo biological treatment, followed by a physicochemical treatment stage before final discharge.

Scenario 2 represents the substitution of the conventional biological and physicochemical wastewater treatments with an electrochemical treatment for the 70% of wastewater generated during the dyeing stage. The remaining 30% of water discharged from the centrifugation process continues to be treated through the conventional physicochemical process.

In this configuration, the hydrogen (H_2) produced as a by-product of the electrochemical reactions is not recovered or valorized. It is assumed to be released and therefore does not contribute to energy substitution within the system. Consequently, the net energy balance reflects only the electricity demand of the electrochemical process with-

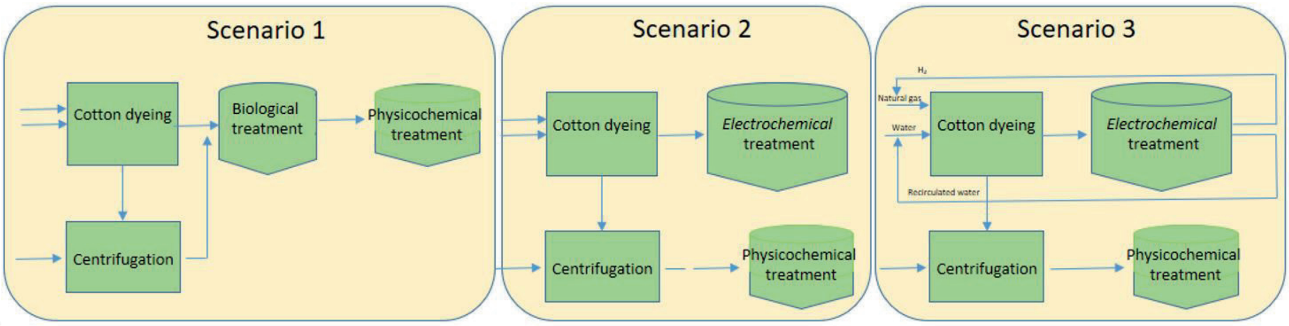

FIGURE 1: Schematic representation of the three study scenarios.

out accounting for any potential energy credits from hydrogen recovery.

Scenario 3 builds upon Scenario 2 by integrating resource recovery strategies. In addition to the electrochemical treatment, a closed-loop water recirculation system is implemented. The treated effluent exits the electrochemical reactor at approximately 60°C, enabling heat recovery and reintegration into the dyeing process, thereby reducing thermal energy demand.

Moreover, approximately 70% of the chemical auxiliaries (e.g., sodium carbonate and salts) remain in the treated stream and are recirculated into the system. The dye is not recirculated, as it is removed during the electrochemical process through indirect oxidation mechanisms involving chlorine species generated in situ.

In this scenario, the hydrogen (H_2) generated at the cathode is recovered and injected into the natural gas stream used in the dyeing process. This partial substitution contributes to a reduction in fossil fuel consumption and associated greenhouse gas emissions.

Additionally, the electrochemical operating conditions (voltage and current density) are optimized to maximize hydrogen production efficiency while maintaining adequate pollutant removal performance. This optimization improves the overall environmental and energetic performance of the system.

The energy mix assumed corresponds to the European electricity mix for the reference year 2024, reflecting average grid composition and emission factors. This assumption is critical, as regional variations in energy sources (renewables vs. fossil fuels) can significantly alter both the carbon footprint and the global warming potential results.

Regarding the choice of data for the LCA, this study comprises the use of both primary data coming from industry and secondary data, from commercial datasets, Primary data includes measurements collected directly from industrial operations and pilot-scale dyeing processes, including measured water consumption (10–300 L/kg), cotton-specific averages (120 L/kg), and effluent characteristics. Secondary data were obtained from established LCA databases (e.g., Ecoinvent, LCA for Experts) and peer-reviewed literature, which provide emission factors, energy mix data, and background processes.

The environmental characterization is performed considering a pool of different impact categories, as suggested by Product Environmental Footpring Category Rules for Apparel and Footwear (PEF Apparel & Footwear, 2025) he inclusion of human health impacts and global warming potential broadens the scope of the analysis, allowing for a more holistic evaluation of the environmental performance of textile dyeing. This framework highlights critical hotspots in resource use, pollutant discharge, and climate-related emissions, while also providing a basis for assessing alternative technologies such as electrochemical treatment.

The Life Cycle Assessment (LCA) methodology, following ISO 14040-44 (Figure 2), has been applied to assess the environmental impacts and benefits associated with the

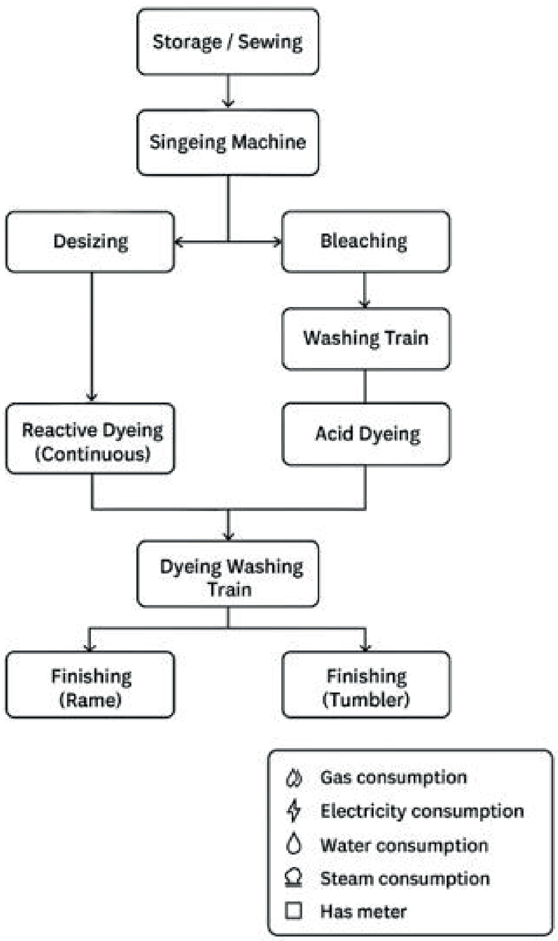

FIGURE 2: LCA process (ISO 14040).

three scenarios. LCA is a systematic approach to evaluate the environmental aspects and potential impacts of a product, process, or system throughout its entire life cycle. The aim of this study is to provide a comprehensive quantitative view of the scenarios and determine their performance in terms of environmental sustainability.

The study was conducted in two main LCA stages:

- Description (Goal and Scope Definition): This stage provides a qualitative description of the processes for the three scenarios, which is complemented with schematic representations. The objective is to compare the three scenarios and evaluate the benefits of water recirculation. The system boundaries, functional unit, and main assumptions are also defined in this stage.
- Inventory Data (Life Cycle Inventory, LCI): This stage specifies the type of data used rather. Primary data were obtained directly from the plant operations, while secondary data were sourced from commercial LCA databases. The LCA calculations were performed using the software LCA for Experts (formerly known as GaBi) from Sphera, together with the following commercial databases for secondary data: Professional, ecoinvent, among others.

The research is conducted by analyzing the dyeing process of the company ABSA (Figure 2) and following the ISO 14040 and 14044 guidelines for the application of LCA. Three scenarios are defined and presented in detail, with a functional unit of 100 kg of dyed cotton fabric.

Scenario 1: As previously mentioned, this scenario corresponds to the conventional process with biological and physicochemical treatment (Figures 3). It represents the current industrial practice at ABSA. The process includes the standard dyeing operations, followed by biological treatment and subsequent physicochemical treatment of the generated wastewater streams. No water recirculation or resource recovery strategies are applied in this configuration. This scenario serves as the baseline for comparison, , enabling the quantification of the environmental impacts associated with the existing production system and providing a reference point against which the performance improvements of Scenarios 2 and 3 can be assessed.

Scenario 2: As previously seen, it involves the replacement of the conventional treatment with an electrochemical process achieving 95% decolorization (Figure 3). The electrochemical process also generates hydrogen as a by-product, while consuming electrical energy for its operation. All other steps of the dyeing process remain the same. This scenario allows evaluation of the environmental benefits and potential trade-offs associated with implementing the electrochemical technology compared to the conventional approach.

Scenario 3: Building on Scenario 2, this stage incorporates the reuse of treated water in subsequent dyeing processes (Figure 3). The use of recirculated water reduces overall fresh water and chemical consumption by 70%, significantly lowering the environmental footprint of the operation. Additionally, the hydrogen generated during the electrochemical treatment is injected alongside natural gas, further decreasing fuel consumption. Energy efficiency is also improved by recovering heat from the electrochemical process discharge, which remains at 60°C. Since the dye-

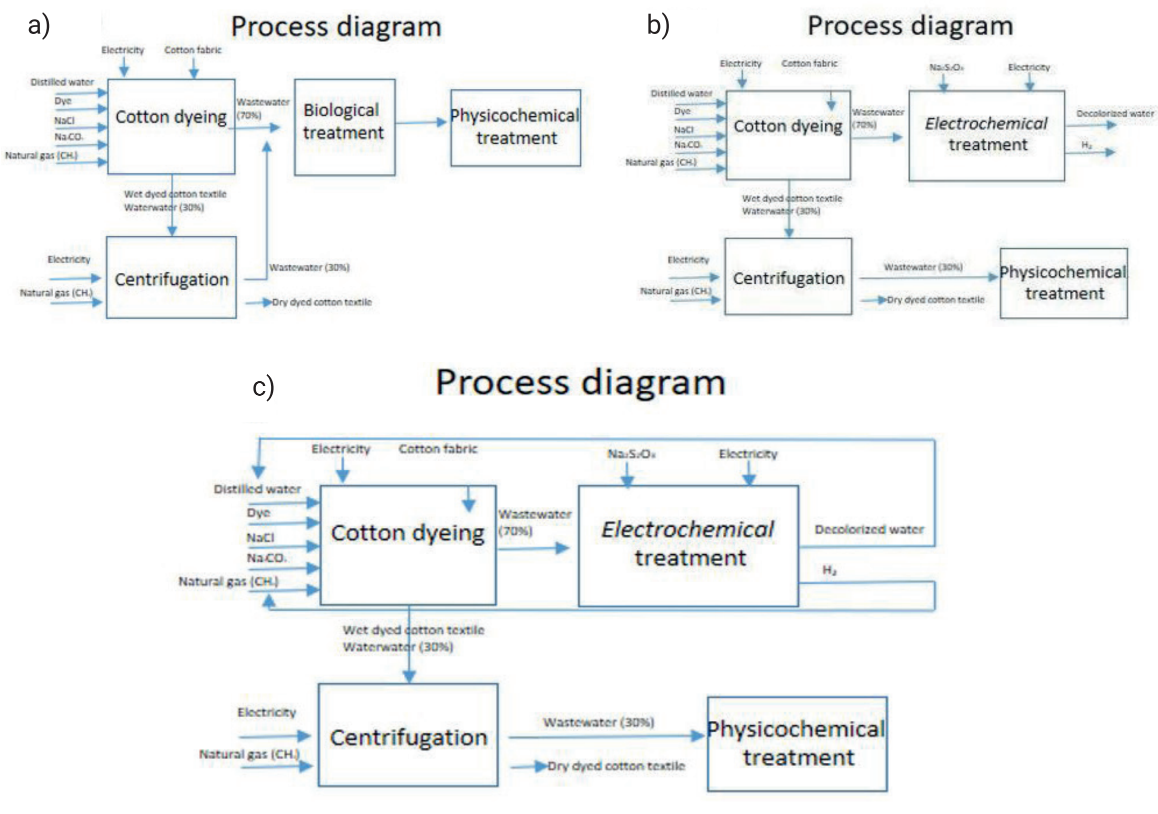

FIGURE 3: Flow diagram from ABSA company (https://absa.es/).

TABLE 1: Data from the three scenarios.

Dyeing process		Scenario 1	Scenario 2	Scenario 3
INPUT	cotton textile (kg)	100	100	100
	Electricity (MJ)	97.8	97.8	97.8
	Distilled water (L)	1000	1000	300
	Dye (kg)	3	3	2.1
	Sodium Chloride (NaCl) (kg)	70	70	21
	Sodium Carbonate (Na_2CO_3) (kg)	20	20	6
	Thermal energy (CH_4) (MJ)	432	432	130
	Decolorized water (reused) (kg)	0	0	700
	Heat of the water (MJ)	0	0	337
	Thermal energy(H_2) (MJ)	0	0	34.6
OUTPUT	Wastewater (L)	764	764	764
	Dyed wet cotton fabric (kg)	429	428	429

ing process requires higher temperatures, this pre-heated water (representing 70% of the total volume) only requires a 20°C increase, drastically reducing natural gas demand. As in Scenario 2, the electricity required for the electrochemical process is fully accounted for in the LCA. This scenario evaluates the benefits of both the technological upgrade and the resource recirculation strategy.

For each scenario, material and energy inputs and outputs were modeled using the LCA for Experts software, including electricity, natural gas, water, salt, and sodium carbonate consumption, as well as by-products such as the hydrogen generated (Table 1). The system boundaries encompass the dyeing and centrifugation processes, the environmental impacts of biological, physicochemical, and electrochemical treatments, and the final disposal of residues, providing a comprehensive assessment of the operational environmental impacts for each scenario. As we can see, the description of Scenario 3 has been updated to explicitly highlight the significant reduction in inputs required for the optimized system. Specifically, the table 1 now clearly reflects that fresh water consumption is reduced from 1,000 L in the baseline to 300 L in Scenario 3. Furthermore, the required amount of NaCl is decreased from 70 kg to 21 kg. These substantial reductions directly emphasize the efficiency and environmental benefits of the closed-loop system implemented in this scenario.

In addition to the environmental assessment, this study also considers the potential economic improvements, particularly the savings achievable through optimized dyeing processes in terms of reduced water, energy, and chemical consumption.

3. RESULTS AND DISCUSSION

The dyeing process (Figure 4) for cotton fabrics comprises a sequence of carefully designed steps aimed at achieving a uniform and durable coloration. It begins with the preparation of a dye bath containing demineralized water, the selected dye, sodium chloride (NaCl) and sodium carbonate (Na_2CO_3), where the demineralized water prevents the formation of precipitates that could compromise dye quality, the dye type (commonly reactive dyes for cotton) is chosen according to the desired color and process, sodium chloride promotes dye fixation by reducing the solubility of the dye in water and enhancing its absorption by cotton fibers, and sodium carbonate acts as an alkaliz-

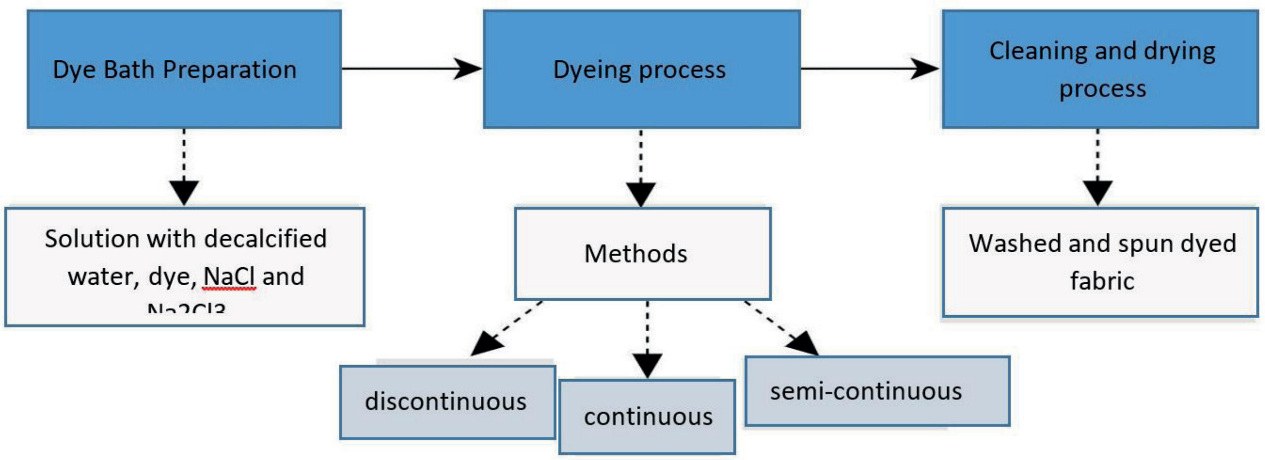

FIGURE 4: Diagram of the conventional process.

ing agent that activates the dye's reactive groups and facilitates chemical bonding with the fibers. Once prepared, the cotton fabric is immersed in the bath under constant agitation to ensure uniform color distribution, and the solution is heated, often using thermal energy from natural gas combustion, to reach the optimal temperature for dye–fiber reaction, which may require several hours depending on the dye type and desired shade. Different dyeing methods can be employed, such as the traditional discontinuous or batch process (which can produce between 5 and 20 tonnes of fabric per day), the continuous process, where production rates range from 30 to 100 tonnes per day, and semi-continuous approaches like the "pad-batch" method, where the fabric is impregnated with dye, rolled, and stored to allow color fixation before washing. Regardless of the method used, dyeing is highly water-intensive: for every 100 kg of dried cotton fabric produced, approximately 1,000 liters of water are consumed. After dyeing, the fabric is rinsed to remove unfixed dye, a critical step for ensuring colorfastness during washing and wear, and is then centrifuged to eliminate as much residual water as possible before subsequent finishing operations (Mazharul Islam K., 2012 and FDTEXTIL 2020).

In addition to the environmental considerations, the three scenarios also incorporate potential economic improvements. In the first scenario, representing the current factory process, costs are mainly associated with biological and physicochemical treatments, which require significant operational expenditures in energy, chemicals, and sludge management.

In the second scenario, the substitution of conventional treatments with electrochemical process introduces opportunities for cost savings through reduced chemical consumption and the added value of hydrogen generation, which can be utilized as an energy carrier.

The third scenario further enhances economic performance by reusing treated water, recovering salts and dyes, and injecting the generated hydrogen together with natural gas, thereby reducing both raw material costs and fossil fuel dependency. These potential savings highlight the dual benefit of the proposed technological alternatives, combining environmental impact reduction with improved economic efficiency.

The conventional cotton fabric dyeing process involves four main stages: dyeing, centrifugation, biological wastewater treatment, and additional tertiary physico-chemical treatment. The latter two are essential for removing residual organic and inorganic contaminants. Biological treatment promotes the growth of microorganisms that degrade organic compounds, while tertiary physico-chemical treatment (typically using activated carbon or coagulation-flocculation) removes residual color. Following these steps, water undergoes sedimentation, filtration, and disinfection before being discharged or reused (Martínez-Huitle, C. A., & Brillas, E., 2009 and Cuesta i Mota, D.,et al. 2024b).

The study evaluated the replacement of these post-dyeing treatment stages with a single electrochemical treatment process. This technology applies direct electric current in an electrolytic cell containing an anode and cathode immersed in alkaline wastewater from dyeing, rich in dyes, NaCl, and Na_2CO_3. Electrochemical oxidation at the anode produces hydroxyl radicals and oxygen, which effectively degrade dyes and complex organic contaminants. At the cathode, water reduction generates hydrogen gas, a potentially valuable by-product. Additionally, chlorine generated from chloride ions can form hypochlorite under alkaline conditions, enhancing dye oxidation (Martínez-Huitle, C. A., & Brillas, E., 2009 and Cuesta i Mota, D.,et al. 2024b).

Depending on current density and treatment time, electrochemical processing can partially break down dye molecules (decolorization) or fully mineralize them to ensure water quality suitable for reuse. Full mineralization requires higher energy input than decolorization alone (Cuesta i Mota, D.,et al. 2024b).

The process also produces ~0.016 kg of hydrogen per 100 kg of fabric, equivalent to 9.9 MJ of energy, offering potential partial substitution for natural gas in heating applications (Figure 5). While hydrogen reuse in this context has not yet been implemented, its integration would require efficient capture and storage systems, adaptation of heat-

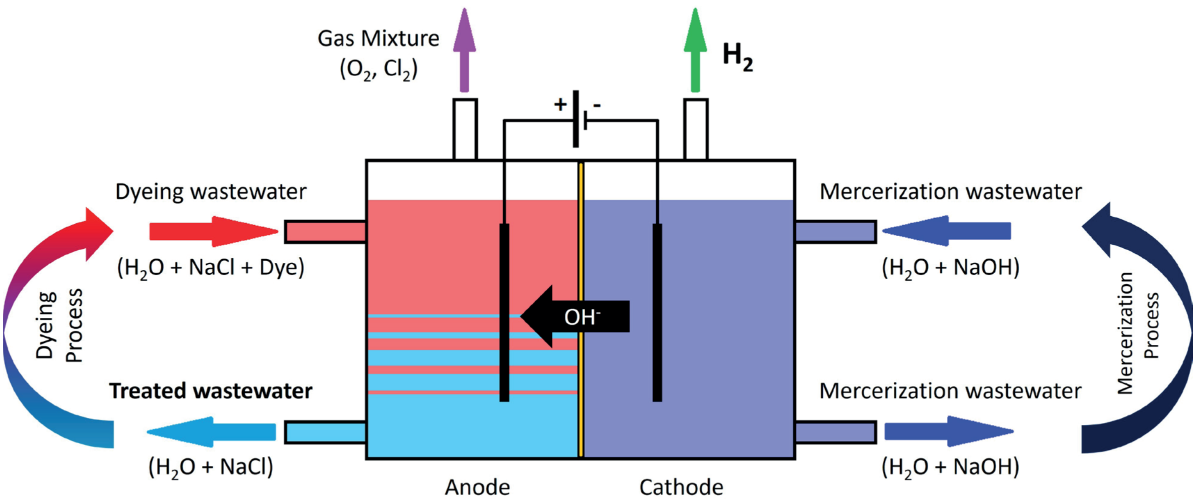

FIGURE 5: Flow diagram of the electrochemical treatment process..

ing equipment to hydrogen fuel, and process optimization to maximize production (Zeng, K., & Zhang, D., 2010).

Life Cycle Assessment (LCA) results indicate that incorporating electrochemical treatment reduces effluent pollutant load and eliminates the need for additional physico-chemical treatment. In Scenario 2, chemical consumption decreases significantly, whereas Scenario 3 achieves the highest savings in water and salts, also reducing water footprint. Overall, Scenario 3 demonstrates the lowest total environmental impact and the greatest resource efficiency.

Figure 6 illustrates the schematic layout of the three study scenarios . As depicted in the graph, Scenario 1 (blue line) represents the current conventional process, serving as the baseline for comparison. In contrast, Scenario 2 (orange line) shows a significant increase in environmental impacts, particularly in Global Warming Potential (GWP) and Acidification Potential (AP), due to the high electricity consumption of the electrochemical process without resource recovery. Finally, Scenario 3 is designed to mitigate these impacts through a closed-loop system, utilizing recovered heat, chemicals, and hydrogen to drastically reduce the overall environmental footprint across most impact categories compared to the other two scenarios.

Figure 7 illustrates the comparative results of the three scenarios regarding water consumption, primary energy demand, and Global Warming Potential (GWP). As shown,

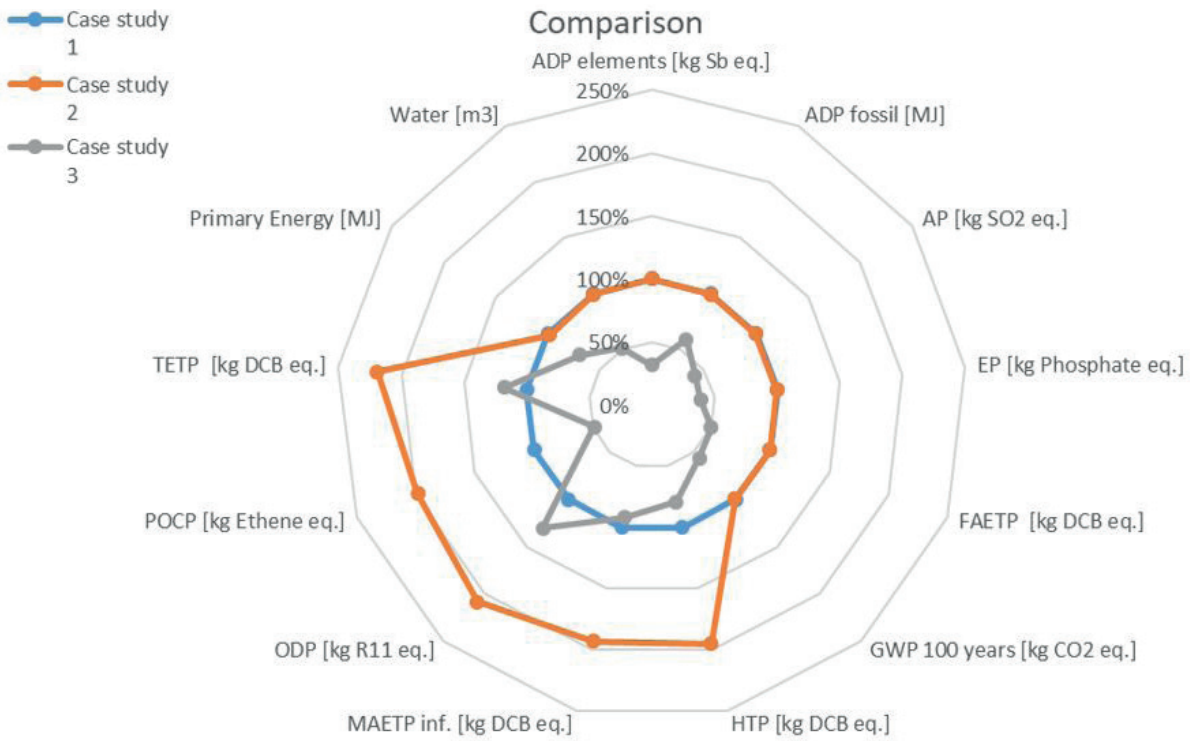

FIGURE 6: Flow diagram of the electrochemical treatment and reuse process.

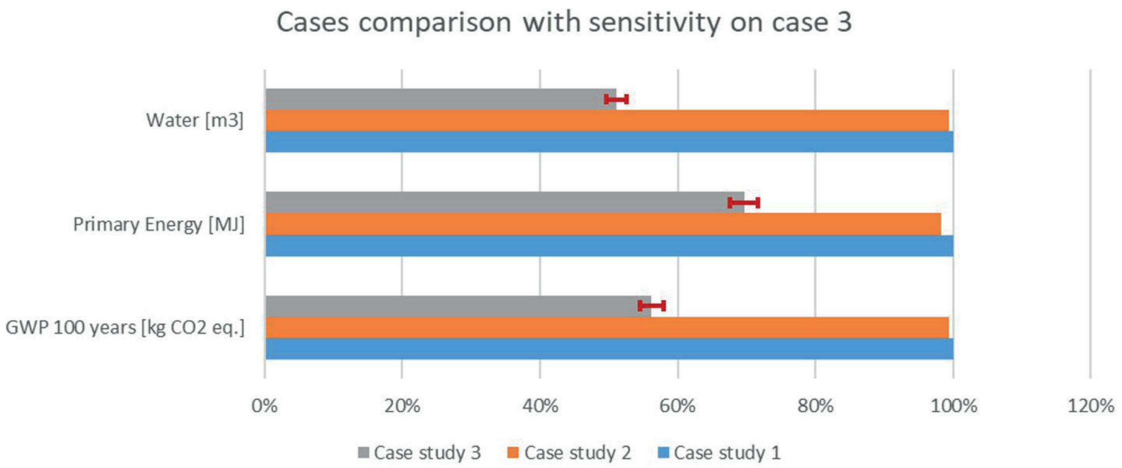

FIGURE 7: Dyeing process.

Scenario 3 (grey bar) demonstrates the most significant improvements, achieving a 50% reduction in water usage and a substantial decrease in GWP compared to the baseline Scenario 1. The red error bars on Scenario 3 indicate the sensitivity range of +-20% with respect to the energy consumed in the electrochemical process

Based on the analysis of Figure 8, the results demonstrate distinct environmental profiles for each scenario, highlighting the impact of each system process. When examining the processes individually, the dyeing stage consistently presents the highest impact across all scenarios and indicators due to energy and chemical consumption. This is followed by the centrifugation stage, which shows a lower relative impact. In terms of wastewater treatment, substituting the conventional biological and physicochemical treatment with electrochemical treatment significantly increases energy-related impacts (GWP and Primary Energy) in Scenario 2 due to high electricity demand without resource recovery. However, when this electrochemical process is coupled with heat and hydrogen recovery in Scenario 3, the environmental footprint is drastically reduced, making it the most sustainable option.

In Figure 9, the laboratory setup is presented for evaluating both the quantity of hydrogen recovered and its purity.

As shown in Table 2, the calculations indicate that the implementation of electrochemical treatment with water and salt reuse leads to a reduction in operating costs of approximately 35% compared to the stages without reuse. This corresponds to an estimated saving of €350 per 100 kg of processed fabric when compared to the conventional dyeing process. Extrapolated to an industrial scale, with an average of three dyeing cycles per machine per day, this results in potential savings of around €1,050 per day. However, the investment costs of electrochemical technology

FIGURE 8: Conventional process.

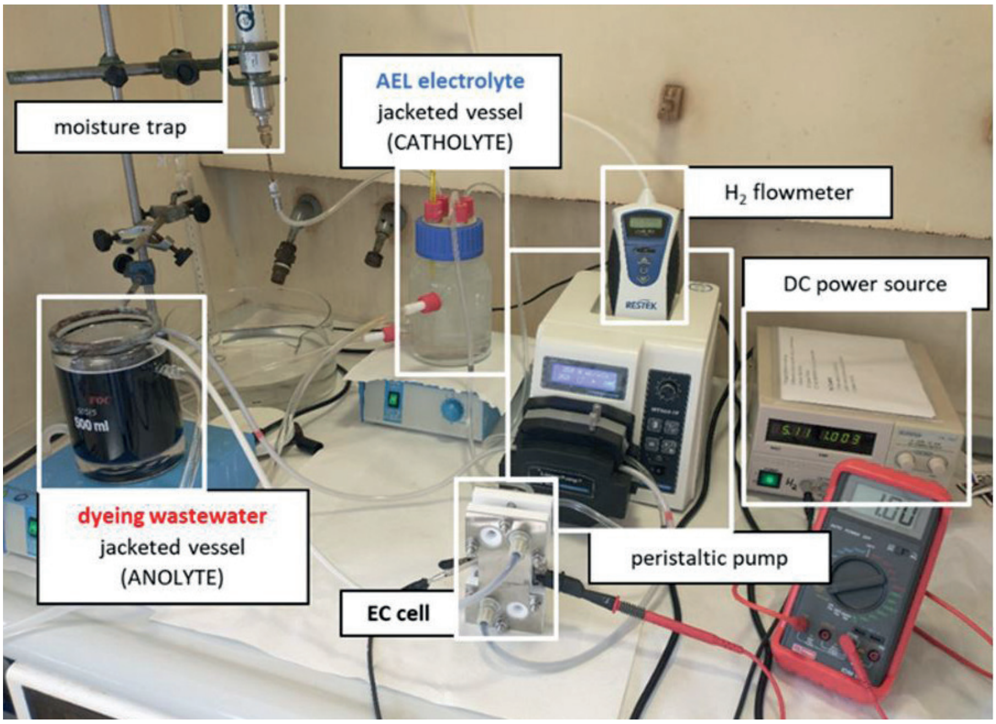

FIGURE 9: Scenario 2: Electrochemical treatment process.

at an industrial scale have not yet been determined, as no commercial reactors for this application are currently available.

This study highlights that transitioning from conventional biological treatments to electrochemical processes with water recirculation (Scenario 3) is the most sustainable path for the textile industry. Key insights include the ability to significantly reduce resource consumption: Scenario 3 cuts freshwater use by 70% (from 1,000 L to 300 L per 100 kg of fabric) and reduces chemical inputs like sodium chloride and sodium carbonate by 70%. Furthermore, electrochemical treatment enables the recovery of hydrogen as a green energy by-product, providing approximately 9.9 MJ of energy per 100 kg of fabric.

The electricity consumption data for the electrochemical treatment used in the inventory were obtained from an experimental prototype. However, the results obtained at a laboratory scale are extrapolable to an industrial scale, as electrochemical technology is highly scalable. Electrochemical technology is highly scalable. At the laboratory scale, an optimal current density is determined. For scaling up to industrial equipment, the ratio between the current and the electrode surface area is maintained. The authors of this article have experience in the industrial scale-up of electrochemical reactors for the treatment of textile dyeing wastewater containing reactive dyes. In the ECUVal project (Eco-innovation project ECO/13/630452), based on laboratory results, they built a reactor with an electrode surface area of 0.6 m² and an optimal amperage of 100 A, which enabled the treatment of 4 m³/h of dyeing effluent (Buscio et al., 2019).

Finally, a sensitivity analysis was performed exclusively on hydrogen production to optimize the generation process by fine-tuning energy consumption.

Figure 10 illustrates the sensitivity analysis for Scenario 3, evaluating the impact of varying the energy consumption required for hydrogen generation by +-5% and +-20%. The graph demonstrates a linear relationship between primary energy input and the resulting environmental impacts, specifically Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP). As depicted, even with a $\pm$20% variation in energy consumption for the electrochemical process, the overall environmental impact remains lower than that of Scenario 2. This indicates that the closed-loop system and resource recovery strategies in Scenario 3 are robust and provide a net environmental benefit regardless of minor fluctuations in energy efficiency. Finally, a sensitivity analysis was performed exclusively on hydrogen production to optimize the generation process by fine-tuning energy consumption. This analysis should be revisited at the industrial scale, as it will provide critical insights for achieving optimal process efficiency and adjustment. This analysis should be revisited at the industrial scale, as it will provide critical insights for achieving optimal process efficiency and adjustment.

TABLE 2: Economical calculation.

	Cost (Euros)		
	Scenario 1	Scenario 2	Scenario 3
Dyeing process	983	983	574.4
Centrifugal process	16.8	16.8	16.8
Electrochemical process	0	0.2	59.5
TOTAL	999.8	1000	650.7

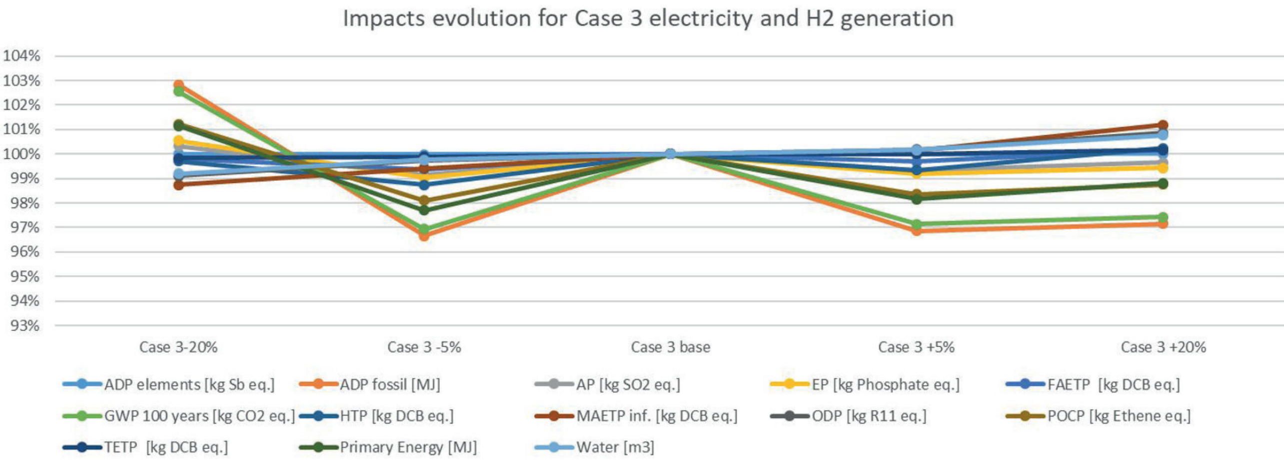

FIGURE 10: Scenario 3: Electrochemical treatment and reuse process.

4. CONCLUSIONS

The implementation of electrochemical treatment in cotton dyeing processes, particularly when coupled with water reuse, provides substantial environmental benefits by significantly reducing water and chemical consumption while enabling the energy valorization of hydrogen. Life Cycle Assessment (LCA) highlights that the reuse of water effectively closes the resource loop, thereby enhancing the overall sustainability of the process. It is advisable that future studies explicitly state, within their methodological sections, which considerations are applied in the initial phases, ensuring greater clarity and traceability throughout the research. This analysis further indicates that the adoption of these technologies at an industrial scale could considerably advance the sustainability of the textile sector, supporting the transition towards a circular economy. Collectively, these findings emphasize the critical importance of developing innovative technologies that not only reduce reliance on natural resources but also promote improved waste management and energy efficiency.

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