Journal of Environmental Chemical Engineering 13 (2025) 118761

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

Environmental sustainability assessment of different strategies for the treatment of wastewater from textile industry

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ARTICLE INFO

Keywords:
Textile wastewater
Hydrodynamic cavitation
LCA
Water enhancement
Biological oxidation
Membrane filtration

ABSTRACT

Severe water consumption and highly polluted wastewater are the main issues of textile industries, which can affect environmental safety. Advanced oxidation processes (AOP) emerged as innovative strategies to enhance conventional wastewater treatments, for their strong ability to reduce chemical oxygen demand (COD) and pollutants. Among these, hydrodynamic cavitation (HC) stands out as a promising technique to minimize the chemical additive uses, thereby improving the process sustainability. A life cycle assessment (LCA) was conducted to compare four scenarios, traditional biological treatment, membrane treatment combined with AOP and HC used either as pre- or post-treatment to the biological process. The results showed that biological process followed by HC offers the lowest environmental impact. This is attributed to a configuration change (compared to HC as pre-treatment) that reduces energy consumption without compromising water quality. In the climate change category, one of the most relevant, HC as a post-treatment (scenario 4) reduces the impact by 94 %, compared to HC pre-treatment (scenario 3). It also achieves around 30 % impact reduction relative to biological treatment, while ensuring the highest water quality, with a 98 % reduction in COD. This quality supports the potential for water recirculation within textile manufacturing. Furthermore, the possibility of water reuse offsets the environmental cost of producing high-quality water, with an average environmental credit between 440 (scenario 3) and 600 (scenario 1) m^3 -world eq, in the water use category. The superiority of the HC post-treatment setup was also confirmed from a performance standpoint, as it reduces the complexity of process management.

1. Introduction

The textile industry is one of the most widespread industrial sectors globally, with a significant presence in both developed and developing countries. This industry is recognized as one of the highest water-consuming sectors, generating large volumes of highly polluted wastewater whose characteristics vary depending on the specific production processes involved [1–4]. The water consumption in the textile industry is associated with the wet processes, such as pre-treatment, dyeing, washing, and printing, which are responsible for the most significant environmental impacts [4–6]. The sector also makes extensive use of chemicals (dyes, softeners, surfactants), which end up in the effluents with the consequent management issue [1,7,8]. The problems related to the presence of chemicals, particularly dyes, include mutagenic and carcinogenic effects, even at low concentrations, in addition to negative consequences for the aquatic ecosystem, food chains and human health [2,3,9]. In this regard, synthetic dyes are classified on the chemical structure basis into azo, phthalocyanine, indigo, anthraquinone, aryl methane and heterocyclic dyes [10]. Their effect on aquatic compartment is linked to their high thermal and photostability, which make them resistant to biodegradation and increase their persistent in the environment. Furthermore, the high concentration in water bodies makes difficult the oxygenation, reducing the biological activity [10]. Several studies also proved effects on human health, including dermatitis, conjunctivitis and disorders to the central nervous system [11]. Textile dye wastewaters can contain partially degraded dye intermediates (aromatic amines) and other xenobiotic compounds which resist biodegradation, enter into the food webs, bioaccumulate, disrupt photosynthesis and exhibit a potential to induce ecotoxic, mutagenic and carcinogenic effects [12,13]. Textile wastewater management is regulated by a complex regulatory framework, which aims to reduce the environmental impact of industrial activities, encourage practices for

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https://doi.org/10.1016/j.jece.2025.118761
Received 3 June 2025; Received in revised form 29 July 2025; Accepted 17 August 2025

the reuse of treated water and promote a more sustainable use of water resources [14]. In this regard, European Directive 2010/75/EU (Industrial Emissions Directive) sets strict limits on the discharge of industrial wastewater, including effluents from the textile sector. This directive requires plants to adopt the Best Available Techniques (BAT) to minimize pollution and ensure that discharges comply with specific limits, thereby helping to protect water quality and the environment in general [14].

Textile wastewater is typically treated through a combination of physical, biological and chemical approaches, alongside innovative techniques, such as hydrodynamic cavitation (HC), each presenting specific advantages and limitations [6,15–18]. Physical treatments are usually the first stage and include sedimentation, flotation, membrane filtration and adsorption to remove both suspended solids and oily substances [15,16,19,20]. However, while effective in reducing the pollutant load, these techniques are not suitable for dyes removal from effluents and often result in significant sludge production, increasing overall process costs [1,21]. Membrane technologies, in particular, offer high separation efficiency for organic and inorganic contaminants, reducing biochemical oxygen demand (BOD5), chemical oxygen demand (COD) and total organic carbon (TOC). These systems operate through a filtration mechanism in which a semi-permeable membrane allows the passage of solvents and small molecules while retaining larger contaminants [15]. Despite advancements, membranes still face significant drawbacks, including fouling, low throughput, and high operational energy demand, along with the generation of secondary wastewater stream [15]. As a result, research efforts have increasingly focused on innovative solutions, such as integrating advanced oxidation processes (AOPs) and developing nanomaterial or ceramic-based membranes, which offer enhanced stability and corrosion resistance, although they still come at a high cost [19,22].

On the other hand, biological approaches include the use of algae, fungi and bacteria with the ability to degrade dyes [6]. The processes allow to obtain high quality effluents by aerobic, anaerobic, and anoxic or facultative or a combination of microorganisms resulting in the degradation of organic matter, reducing COD and other pollutants [6,15]. These treatments are widely used in the textile industry thanks to their low impact, low costs, low resulting waste [15]. However, their efficiency is highly dependent on factors like pollutant concentration, microbial load and operating conditions (e.g. temperature and oxygen concentration) [16,23]. For example, in the case of fungi, which remove dyes through biodegradation and/or biosorption, growth temperature can decrease the active sites and the surface for adsorption [24–26]. Furthermore, bacterial and fungal strains are selective only for specific contaminants and the effectiveness of biological methods relies on the adaptability of the microbes [1,15,23]. Chemical processes, including ion exchange, photocatalysis and AOP, are designed to remove residual pollutants, such as micropollutants, dyes, and heavy metals, that previous treatments fail to eliminate. [19]. AOP, in particular, involve the generation of reactive oxygen species (ROS) with great potential for removing a broad spectrum of contaminants, emerging as a promising alternative to the most common approaches [9,21,27]. Despite their effectiveness, chemical processes are associated with high reagent and energy requirements, and the generation of huge quantity of byproducts. These materials include the intermediates and sludge of the Fenton's reaction, which can hinder the process scale-up [2]. Furthermore, Fenton process is particularly sensitive to the pH variations, and it works in a narrow pH range between 2.5 and 4 [28]. To overcome these limitations, recent research has focused on emerging technologies such as, HC, which can enhance conventional treatment and offer improved performance when combine with oxidative agents [9,18,29–31]. This technique uses the formation and implosion of vapor bubbles within a fluid to generate microregions with extreme conditions of high pressure and temperature. This leads to the formation of high reactive radical species, such as hydroxyl radicals (•OH), which attacks organic molecules, facilitating the decomposition of complex organic molecules and the destruction of resistant pollutants. Thanks to this approach the need for chemical additives can be reduced, improving process sustainability [31]. The combination with oxidizing agents (H_2O_2; O_3) enhances the treatment efficiency and reduces the reaction time [9,29–31]. However, when HC is combined with strong oxidants, degradation does not always occur completely in a single step and some intermediates can be produced such as aldehydes, low molecular weight organic acids, partially oxidized aromatic compounds more toxic than the original substances or other reactive intermediates [30,31]. To prevent the accumulation of toxic intermediates, HC is often combined with AOPs such as UV/H_2O_2 or UV/O_3, Fenton and photo-Fenton, which help fully degrade the intermediates. Furthermore, by adjusting parameters such as pH, reaction time, dosage of H_2O_2 or O_3, it is possible to promote the complete mineralization of intermediates [30,31]. In addition to the process effectiveness, the sustainability is a key aspect in the wastewater treatment field and the life cycle assessment (LCA) analysis is a perfect tool to assess it [5,32,33]. This approach studies the inputs and the outputs of materials and energy throughout the entire life cycle of a product, from raw material extraction to use and end-of-life, including waste collection, segregation, treatment, recycling, and disposal [34,35]. The assessment is performed in agreement with the reference standards UNI ENI ISO 14040:2021 and 14044:2021, considering the aspects of environmental conservation, resource depletion and human health. [36,37]. This work aims at comparing the sustainability level of the innovative HC (with different configurations) with most traditional biological oxidation and an integrated process combining membrane treatments with AOP. The innovation of this work is the application of LCA as a support to validate theoretical processes in the textile wastewater treatment field, highlighting their weaknesses and thus guiding in the optimization to obtain the most sustainable option. The idea is to move beyond the traditional indicators/pollutant-based evaluation (e.g. pollutants, turbidity, odors) or single-point energy estimations and instead assess the actual sustainability of a technique through a more holistic approach [38–40]. The results of the present study represent a breakthrough, since the literature still lacks of sustainability analysis focused on the innovative application of HC method in the textile industry, despite other technics have been previously evaluated [35,41,42]. In this regard, literature reports LCA applied on coagulation-flocculation-Fenton-neutralization (also integrating electrochemical steps) [43], the combination of electrocoagulation and ozonation [5,41], the use of capacitive deionization and reverse osmosis membrane [44] and a high-scale process in India that includes seven operation units, equalization, aeration, clarification, pass through activated carbon filters, ozonation, ultrafiltration and reverse osmosis [35]. The results of the present paper represent an essential part of a funded project titled "Sustainable Management strategies of liquid waste for transition to circular economy through HC technology- HYDROCAVI" (tender TECH- PRIN 2022), which aims at developing innovative solutions in wastewater treatment field, able to integrate technical advantages with sustainability benefits.

2. Materials and methods

2.1. System boundaries

LCA evaluates four treatment scenarios: the conventional biological process (Scenario 1), an integrated treatment combining membrane technologies and AOP (Scenario 2), HC as a pre-treatment (Scenario 3), and HC as a post-treatment following biological treatment (Scenario 4). The system boundaries, reported in Fig. 1, define the input and output flows included in the analysis, based on the mass and energy balances provided by an industrial facility located in Abruzzo, central Italy. All scenarios share a preliminary mechanical screening step, which removes coarse solids such as stones and rags from the influent. Subsequent wastewater treatments differ according to each scenario, as indicated by the distinct colors in Fig. 1 (each scenario corresponds to a different

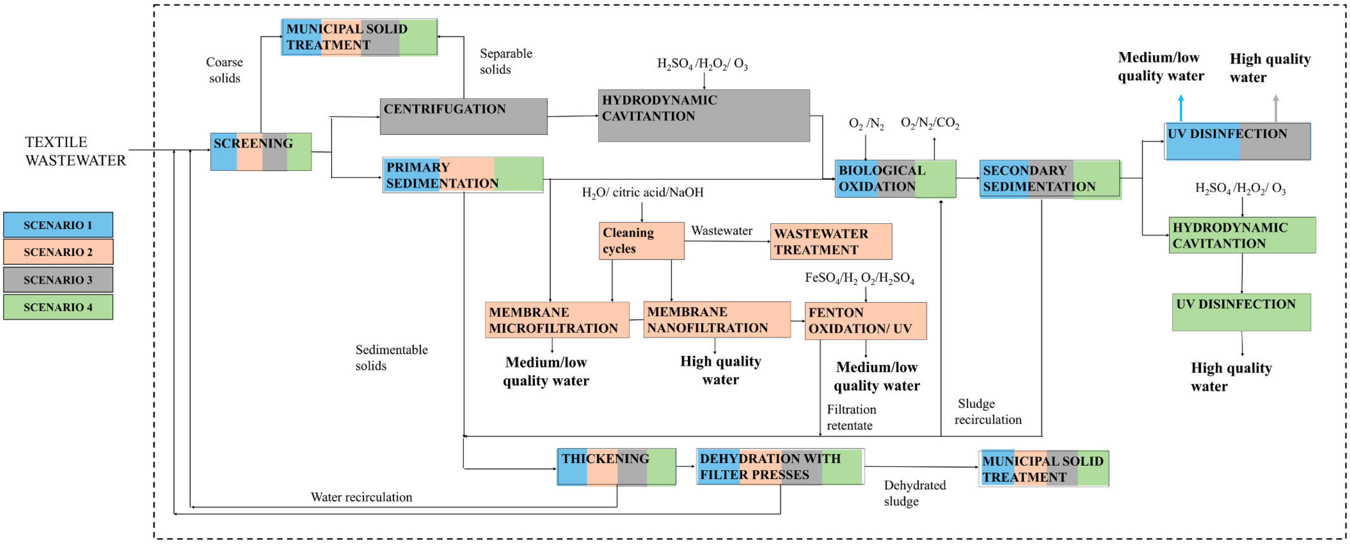

Fig. 1. System boundaries of different scenarios. Each scenario is identified by a different color.

color). After the preliminary screening phase in scenarios 1 and 4, the effluent passes through two primary sedimentation tanks, where additional coarse solids and approximately 85 % of fine solids are removed and ends up in the oxidation tank. In scenario 3, the effluent is first processed by a centrifuge to separate remaining solids, and then treated in a Venturi tube, where HC occurs in combination with oxidizing agents, according to Ayedi et al. [18]. Post-cavitation, the effluent is fed into an oxidation tank, similarly to scenarios 1 and 4, where biodegradation of organic matter is performed by heterotrophic and nitrifying bacteria present in the biomass. After the oxidation tank, in scenarios 1, 3 and 4 the effluent is sent to the secondary sedimentation tank for biomass separation from the clarified water. Approximately 75 % of the biomass is recirculated to the oxidation tank to maintain microbial activity, while the remaining 25 % is sent to the sludge treatment. For disinfection, scenarios 1 and 3 use UV lamps, producing medium/low- and high-quality water, respectively. In scenario 4, the clarified water undergoes tertiary treatment via HC combined with oxidizing agents, prior to UV disinfection. Water quality classifications are based on characterization parameters detailed in the assumptions section. Scenario 2, following Lebron et al., differs significantly: after mechanical screening, the effluent undergoes sequential microfiltration (MF), nanofiltration (NF), and the photo-Fenton process [20]. MF is employed as an essential pre-treatment to remove suspended particles and recover dye from the effluent. The MF concentrate, containing the recovered dye, can be reused in further dyeing processes, while the MF permeate is subsequently treated by NF. NF is an advanced process that further reduces COD and dissolved ions. As discussed in the following paragraph, the NF permeate exhibits optimal characteristic for reuse in more delicate textile processes, whereas the NF concentrate, which contains a high residual organic load, requires further treatment. The NF concentrate is treated through a photo-Fenton process to further reduce residual organic load, resulting in a medium/low-quality water. Furthermore, MF is followed by three cleaning cycles (2 min each) for the membrane regeneration, to guarantee the efficiency of the filtration system: the first one with deionized water, the second one with citric acid (pH 2), and the third one with NaOH (pH 9).

The sludge treatment line is common to all scenarios. Solids from both primary and secondary sedimentation tanks are collected in a thickener for further solid concentration then dehydrated by a belt press, reducing volume and enabling authorized disposal. Clarified water from this process is recirculated to the head of the plant for mixing with the incoming effluent. Additional details on the four scenarios are reported in the supplementary materials.

2.2. Life cycle inventory

Table 1 summarizes the mass and energy balances built to perform the LCA, referred to the selected functional unit of 13,700 kg of textile wastewater, which is the wastewater quantity per hour resulting from a representative Italian textile industry. The selection of this functional unit enabled the estimation of impacts associated with the wastewater treatment at an average textile industry. All results can be easily normalized per functional unit, allowing them to be expressed relative to 1 kg of textile wastewater flow. Both the mass and the energy balances were obtained by the simulation with SuperPro Designer version 9.5, a modelling tool that allows to simulate chemical, biochemical and environmental processes, providing a detailed analysis of the system's performance.

Scenario 1 is the process which requires less input materials compared to the other scenarios, since it only requires the addition of O_2

Table 1
Mass and energy balances referred to the functional unit of 13700 kg/h of textile wastewater.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
INPUT				
Textile wastewater (kg/h)	13700	13700	13700	13700
Energy (kWh)	18	225	861	24
Oxygen (gas) (kg/h)	2		1	3
Nitrogen (gas) (kg/h)	8		4	4
Hydrogen peroxide (kg/h)		2	1	1
Ferrous sulphate (kg/h)		0.4		
Citric acid (1 %)(kg/h)		0.02		
Sodium hydroxide (2 %)(kg/h)		0.01		
Deionized water (kg/h)		2		
Sulphuric acid 96 % (kg/h)		0.03	0.2	0.2
Ozone (gas) (kg/h)			0.1	0.1
OUTPUT				
Oxygen (gas) (kg/h)	0.3		0.6	1
Nitrogen (gas) (kg/h)	8		4	9
Municipal wastewater treatment (kg/h)		2		
Carbon dioxide (gas) (kg/h)	2		0.8	3
Coarse solids (kg/h)	14	14	14	14
Sludge (kg/h)			0.1	
Dehydrated sludge (kg/h)	10	10	10	10
Medium/low-quality water (kg/h)	13700	4930		
High-quality water (kg/h)		8770	13700	13700

and N_2 for biological oxidation. Scenarios 3 and 4, which share with scenario 1 biological oxidation step, require the further addition of H_2O_2 and O_3 to perform HC and H_2SO_4 to decrease the pH of the effluent. On the contrary scenario 2, which does not include the biological oxidation step, requires H_2O_2, $FeSO_4$, H_2SO_4 for Fenton reaction and citric acid, NaOH, and deionized H_2O for membrane cleaning cycles. Citric acid and NaOH solutions used for membrane washing are assumed to have a flow of 10 m^3/year, deriving from the integration of software results with literature data. The energy consumption of Scenario 3 is higher than that of the other scenarios due to the presence of the centrifugation system, which is necessary to avoid clogging or damage to the cavitation system caused by solid particles. Although technically feasible, this operation can significantly affect the process's sustainability at full scale. An alternative to the centrifugation operation could be to replace it with a filtration process; for example, a cartridge filtration system with an appropriate mesh size could represent a feasible and more energy-efficient solution

Some assumptions were made during the material and energy balances estimation. It has been assumed that the solids from screening and centrifugation as well as dehydrated sludges are treated as municipal solid waste, considering their composition. The water resulting from the treatment is classified in two different quality levels on the characterization basis (Table 2). The water properties define their use and destination within the process. More in detail, water resulting from scenario 1 is considered of medium/low-quality and can be reusable within the production process in cleaning operations. For this reason, it is assumed as an environmental credit (with a mathematically negative value), to quantify the avoided impact for water supply. In this regard, the credit aims at quantifying the environmental benefit as the difference between the impact due to wastewater treatment and the potential impact associated with production and supply of the same quantity of fresh water (i.e. traditional primary production). On the other hand, the water resulting from scenarios 3 and 4 is classified as high-quality, due to high removal efficiencies of COD, BOD5 and total suspended solids (TSS) (Table 2). Considering their characteristics, these flows are suitable for recirculation within the production cycle in more sensitive operations, such as washing and rinsing equipment and fabrics. In this case the environmental benefit is estimated as a credit for the avoided production of a deionized water, necessary for the textile manufacturing processes. In scenario 2, water results from MF, NF and Fenton oxidation processes. Water from MF is considered of medium/low quality since the process is effective in filtering colloidal particles, while the residual dyes can pass through the permeate causing an increase in COD and BOD5 (Table 2). MF is often used as a pre-treatment before further filtration steps. Similarly, the concentrate treated by Fenton oxidation, despite a 70 % COD reduction, is considered of medium/low quality due to the residues of Fe ions. These effluents are suitable for less noble uses, such as washing floors or containers, avoiding freshwater consumption. On the other hand, the effluent from NF is characterized by high purity, comparable to water derived from scenarios 3 and 4.

2.3. Software and methods

The LCA was conducted in agreement with the ISO 14040 and 14044:2021 standards [36,37]. The analysis employes the "LCA for Expert" software by Sphera, along with the associated database (My Professional Database 2024.2), to model energy and raw material production processes and quantify the environmental burdens of the evaluated scenarios. Environmental impacts were assessed using the Environmental Footprint (EF) 3.0 method, which includes classification and characterization phase and normalization and weighting phase [45]. This approach considers 16 impact categories (and the related impact indicators) to evaluate a wide range of effects, aiming to capture the full spectrum of potential impacts across supply chains. More in details, 8 categories are related to environmental issues (acidification [mole of H+ eq.], climate change [kg CO_2 eq.], ecotoxicity freshwater [CTUe], eutrophication freshwater [kg P eq.], eutrophication marine [kg N eq.], eutrophication terrestrial [mole of N eq.], ozone depletion [kg C-11 eq.]); 5 categories are related to human health (human toxicity, cancer effects [CTUh], human toxicity non-cancer effects [CTUh], ionizing radiation-human health [Bq U235 eq.], particulate matter [g PM2.5 eq.], photochemical ozone formation [kg NMVOC eq.]), and 4 categories to the resource depletion (land use [C deficit eq.], resource use, fossils [kg Sb eq.], resource use, mineral and metals [kg Sb eq.], water use [m^3-world eq.]).

The results of normalization and weighting phase are expressed in person equivalents (p.e.), in agreement with the EF 3.0 method, representing the average annual impact of a European citizen, covering global to local environmental impacts and resource consumption [46]. The normalization and weighting factors are summarized in Table S1.

3. Results and discussion

3.1. Life cycle impact assessment

The results of classification and characterization step are reported in Fig. 2. Overall, the best scenario is the innovative process with HC as a post-treatment (scenario 4), which provides a high level of water quality with low energy consumption. This process results from a change in the configuration of scenario 3, with cavitation applied as post-treatment, instead of pre-treatment. The benefit is explained by significantly lower energy consumption (maintaining the same quality of resulting water) due to the avoided centrifugation, necessary in scenario 3 as a pre-treatment to avoid problems with the Venturi tube operations. In

Table 2
Characterization of water flows before and after treatment in the considered scenario, carried out using UV–visible spectrophotometry. N.d. means not detectable.

Parameters (mg/L)	Textile effluent input	Scenario 1 Medium/low-quality water	Scenario 2			Scenario 3 High-quality water	Scenario 4 High-quality water
			Medium/low-quality water	High-quality water	Medium/low-quality water		
Volume (m^3/h)	13.7	13.7	2.74	8.77	2.19	13.7	13.7
COD	140.30	56.19	285.95	31.92	112.96	3.02	3.17
BOD5	10.07	2.74	19.87	4.36	18.71	3.93	0.14
TOC	64.50	44.33	771.68	43.07	110.77	42.6	34.93
Sulfates	172.6	135.6	164.4	28.41	0.24	43.62	50.78
Cationic surfactants	0.18	0.13	1.11	0.18	0.13	0.05	0.07
Anionic surfactants	1.10	0.55	n.d.	0.71	0.46	0.31	0.41
Non-ionic surfactants	2.57	1.15	0.18	0.92	0.76	0.72	0.95
Phosphates	0.25	0.26	0.24	0.27	0.24	0.18	0.18
Total fine solids	610	3.8	91.63	0.99	0.55	0.79	3.33
Coarse solids	1010	n.d.	n.d.	n.d.	n.d	n.d.	n.d.

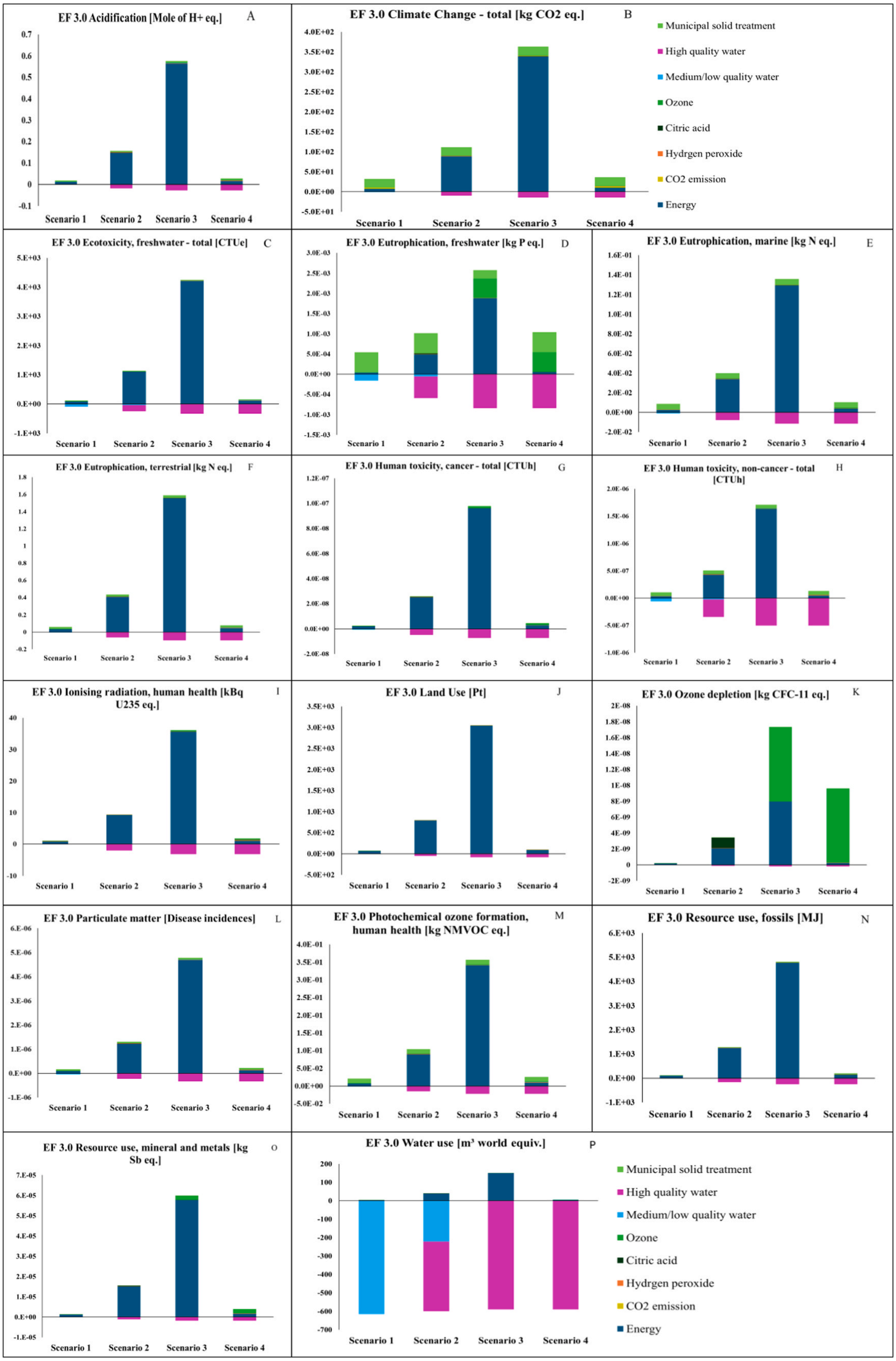

Fig. 2. Results of classification and characterization. The contribution of oxygen, nitrogen, ferrous sulphate, sodium hydroxide, deionized water, municipal wastewater treatment and sulphuric acid are under 3 % and not detectable in the figure, so they have been omitted from the legend.

scenario 4 the settler use makes the centrifugation superfluous (as confirmed by the characterization in Table 2). This improvement in process configuration is translated into an impact of scenario 4 that is less than half of that resulting from scenario 3 in all the considered categories. In the climate change category, which represents the index of potential global warming due to emissions of greenhouse gases to the air, the decrease of electricity demand in scenario 4 allows a whole impact reduction of 94 %, compared to scenario 3 (22 kg CO_2 eq. vs. 348 kg CO_2 eq. Fig. 2B). The burden due to energy supply is linked to a specific grid mix, and it varies based on the country where the processes are carried out. In the present study it was used the Italian energy grid mix, where natural gas is the main resource (48 % of the whole mix), explaining the effects on most of the impact categories. Natural gas has lower CO_2 and methane emissions than coal or oil per unit of energy produced, but it contributes significantly to climate change category (Fig. 2B). The results look promising (irrespective from the selected option) if compared with those reported by literature that reach 47.5 kg CO_2 eq/m^3 [43], compared to 2.2 kg CO_2 eq/m^3 of scenario 1, 7.4 kg CO_2 eq/m^3 of scenario 2, 25.4 kg CO_2 eq/m^3 of scenario 3, 1.6 kg CO_2 eq/m^3 of scenario 4. Scenarios 1 and 4 also result more sustainable than the process described by Nakhate et al. with impacts variable between 4.1 and 6.0 kg CO_2 eq/m^3 [35]. The effect of natural gas combustion for electricity production is also visible on other categories; indeed, during combustion it also generates NOx which contributes to acidification (Fig. 2A), eutrophication of aquatic and terrestrial ecosystems (Fig. 2C, E and F) and formation of tropospheric ozone (Fig. 2M). The main impacts on human health are given by the potential release of toxic substances, such as methane or other volatile substances, during extraction and distribution (Fig. 2G and H). Furthermore, natural gas is a non-renewable fossil resource, so its use leads to the depletion of available resources (Fig. 2N and O).

On the other hand, the main issues of scenario 4 are related to the management of the resulting solid waste, classified as municipal solid treatment, and to the use of ozone (in the categories of ozone depletion Fig. 2K and resource use, mineral and metals Fig. 2O), while the impact of energy is relevant only in the land use category (Fig. 2J). The impact of solid waste management is mostly highlighted in the categories of climate change (Fig. 2B), eutrophication (Fig. 2D and E) and photochemical ozone formation (2 M), due to the processes that take place during the decomposition of organic matter and the management of the landfill itself. In more detail, greenhouse gas emissions from the decomposition of organic matter in sludge and operational processes at landfills contribute to the climate change category, while the release of nutrients, such as nitrogen and phosphorus, into landfill percolating water or in the form of ammonia impacts eutrophication categories. In addition, gaseous emissions can also contribute to the formation of ozone.

Further studies should be carried out to explore the potential added value of recovering the dehydrated sludges, or to optimize the costs associated with their disposal, making the water treatment process even more environmentally sustainable. Overall, Scenario 3 turned out to be the least advantageous treatment, also compared to scenario 1 and 2. As concern scenario 2, the main issue is the electricity demand for cleaning operations of the membranes, which involve pumping cleaning fluids, and the necessity to maintain high operative pressure. On the other hand, the burden due to cleaning chemicals (NaOH and citric acid) is not significant, also hypothesizing its doubling in the perspective of a process scale-up. The burden of energy consumption is reflected in all the impact categories for both scenario 2 and 3 and it is not offset by the environmental credits deriving from the possibility to obtain high-quality water, suitable to be recirculated in production processes. The environmental benefit for water recovery is mostly highlighted in water use category (Fig. 2P), which is an indicator of the relative amount of water used, based on regionalized water scarcity factors. It is evident that the credit differs between medium/low-quality water and high-quality water, based on the different treatment process required for groundwater to reach the desired quality. The recirculation of medium/low-quality water in scenario 1 avoids the impact associated with the supply of additional water, which would need to be treated through screening, sedimentation, coagulation, decarbonization, disinfection, chlorination, and filtration processes to achieve the same quality. Similarly, in scenarios 3 and 4, the recirculation of the same amount of water prevents an impact due to the avoided use and treatment of groundwater through the reverse osmosis process. This results in an average environmental credit of 6×10^2 m^3 -world eq., which represents a cubic meter consumed on average worldwide, in exchange of a water footprint of 4.6 (scenario 1), 40.6 (scenario 2), 151.1 (scenario 3) and 5.9 (scenario 4).

Classification and characterization phase is supported by the normalization and weighting, which provides an overall view of the sustainability of the four scenarios, making the different categories comparable. Indeed, the results are referred to reference values and expressed in a normalised and homogeneous manner (p.e.). The further weighting factors reflect the perceived relative importance of the life cycle impact categories considered. This approach is intended to establish a hierarchy of priorities in sustainability actions rather than downplaying certain environmental issues. Fig. 3 confirms the interpretation of classification and characterization, with scenario 4 as the best option and scenario 3 as the worst one.

In this case, the normalization and weighting steps mainly allow to assess the difference among the credits value in the different categories, showing a comparable result for the four scenarios. The credits can completely offset the burdens process only in the cases of scenario 1 and 4, with values around -4×10^{-3} p.e. against 1.5×10^{-3} p.e. resulting from impacts (Fig. 3).

This result is explained by the pie-charts, which identified climate change as the most affected category (mainly in scenarios 1 and 4, respectively around 60 % and 52 % of the whole impact), and the water used as the most saved category (Fig. 3, pie-charts).

3.2. *Sensitivity analysis*

The sensitivity analysis, in the LCA context, consists of studying the variations in impact values as one or more contributing factors change, in agreement with the LCA ISO standards. The energy and the solid waste disposal were selected in the present analysis as factors to vary, considering their impact on the whole environmental burden of scenarios. The variation effect was assessed on the climate change category, identified as the most affected by normalization and weighting (Fig. 3) and it is shown, in Fig. 4, as the difference between environmental impacts and credits for each scenario.

As concern the electricity, the Italian grid mix was substituted by a European grid mix, where the most relevant sources are nuclear (24 %), natural gas (21 %) and wind (15 %) or the completely renewable energy production by photovoltaic.

As shown in Fig. 4A, European grid mix does not result in significant variations in the total impact, compared to the Italian energy mix. On the contrary, replacing the Italian mix with photovoltaic energy leads to a significant impact reduction across all scenarios, mainly in the highly energy-consuming scenarios 2 and 3, where the decrease exceeds the 80 %. The integration of photovoltaic on the industry rooftops is a common and promising practice in the Mediterranean area, where the climate conditions are favorable [47]. Furthermore, the renewable energy production by solar panels could be an interesting solution in the areas characterized by intermitted electricity, to improve the accessibility to the innovative technology.

The other considered aspect was the possibility to decrease the solid waste to manage. Indeed, textile wastewater treatment generates large quantities of organic sludge, whose disposal entails high costs and environmental risks, including toxic emissions and soil contamination. The industrial sludge reuse has recently been evaluated by some authors, proving its enhancement in bioenergy and fertilizer fields [48].

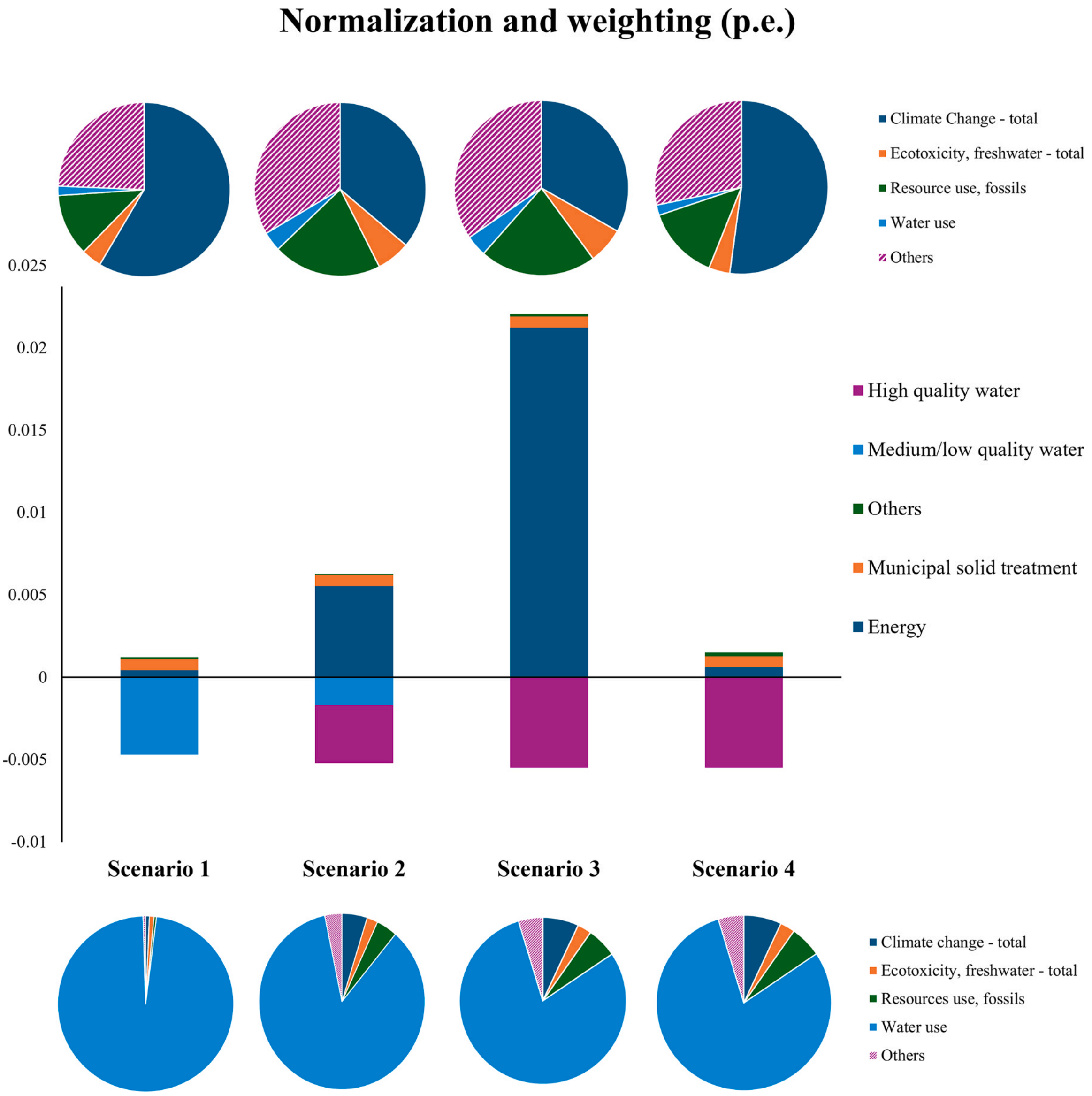

Fig. 3. Results of normalization and weighting phase. The pie-charts on the top show the contributions on the impact categories. The two legends report the categories with impact greater than 5 %, while the other categories are grouped together under "Others".

The exploitation as fuel to generate energy is considered by several authors such as Gadhi et al. (2024) and Hossain (2025) [49,50], while other studies evaluated the potential use as a supplementary cementitious material after pretreatment, like calcination and grinding on textile sludge for achieving excellent results [48,51,52]. The literature reports further examples of textile sludge applications for valuable products manufacturing, such as adsorbent materials [52,53]. For this reason, the second step of sensitivity assessed the scenario impact variations avoiding the sludge management aspect from analysis (assuming its enhancement, with impact). As reported in Fig. 4B, the avoided waste disposal should allow a positive effect mainly on scenario 4, where the balance between impact and environmental credits should become close to 0, further enhancing the benefit of HC as post-treatment. Additionally, in scenario 2, it is important to consider the presence of Fe oxide precipitates derived from the photo-Fenton treatment in the sludge produced during the process, making necessary to assess whether the sludge can be recovered and reused in other industrial contexts.

Overall, the sensitivity analysis confirmed scenario 4 as the best approach, irrespective of the factor variations. Furthermore, the effect of the variation of the two factors on the climate change impact was assessed through the Monte Carlo method (implemented in RStudio software) by 1000 simulations varying the possible substitution of electricity grid mix with photovoltaic energy from 0 % to 100 % and the possible solid waste exploitation from 0 % to 100 %. As it can be seen the combination of a 50 % of integrated photovoltaic and the avoided disposal of solid waste is the minimum condition to offset the impact by the environmental credits (environmental credit greater than scenario impact) (Fig. 4C).

The robustness of the included processes was evaluated by a Pedigree matrix which assesses reliability, completeness, temporal correlation, geographical correlation and technological correlation giving a qualitative score from 1 (the best one) and 5 (the worst one) [54]. All the considered processes have a score between 1 and 2, and they are considered reliable. Possible variability due to the impact categories is not considered relevant for the comparison among the four scenarios since they were assessed by the same method (EF 3.0).

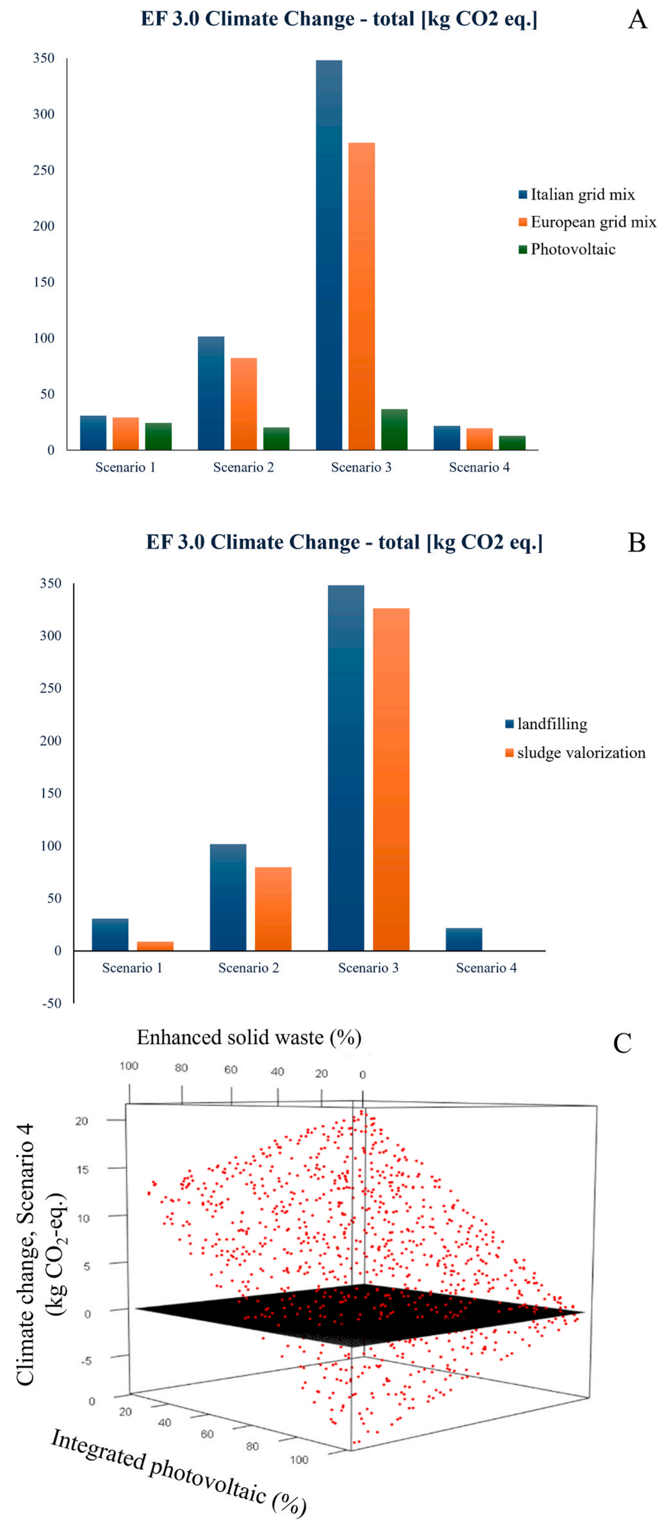

Fig. 4. Impact on climate change category as a function of the variation in electricity grid mix (A) and sludge management (B), and integration of the growing use of renewable energy and solid waste enhancement (C).

3.3. Comparative analysis of the qualitative performance of the four scenarios

Sustainability is a key aspect for the development of innovative processes but its integration with the performance of the treatments is essential for the success of its further scale-up. With this aim, Table 3 assesses the quality of the four considered scenarios, considering key parameters in the perspective of a sustainable scale-up: treated water quality, energy consumption, the possible uses of resulting water and the complexity of process management. The choice of these parameters stems from the need to balance treatment effectiveness (water quality) with operational and energy efficiency.

The results of the assessment prove that HC as a post-treatment (Scenario 4) is the most advantageous option, supporting the sustainability achievements (Table 3). Indeed, this process setup provides high-quality water, comparable to HC as pretreatment, but with lower energy consumption, primarily because it avoids the use of energy-intensive centrifuges (Fig. 5). Fig. 5 provides a detailed comparison of the annual energy consumption required by the different scenarios. From an energy efficiency perspective, scenarios 1 and 4 are clearly the most sustainable, with annual consumption below 250,000 kWh. In contrast scenarios 2 and 3 require drastically higher energy inputs, with scenario 3 consuming almost 36 times more energy than scenario 4 (Fig. 5). It should be noted that the high energy demand associated with centrifugation in Scenario 3 could negatively affect the scalability of the process at full scale. Therefore, the elimination of the centrifuge in Scenario 4 not only improves energy efficiency but also represents a key advantage in terms of process feasibility for industrial implementation. In this context, a possible improvement in process control and performance could be obtained by integrating the real-time monitoring systems, such as IoT-based sensors for COD and BOD. Moreover, the implementation of a field-scale pilot trial is recommended to validate the proposed configuration under real conditions, check and verify the results in terms of degradation yield and confirm the scalability.

The final water quality obtained by different scenarios was compared with the international discharge and/or reuse standards from Europe, the USA and India (Table 4). For water reuse, the analysis focused on the agricultural sector, which is one of the most regulated and monitored worldwide, particularly on water reuse for the irrigation of crops consumed raw. Among the evaluated parameters, COD is not always mandatory but provides useful supporting indications about water quality. Limits can vary within the same country (for instance, California has stricter requirements than the rest of USA, and some Indian states have their own regional standards). From this comparison it emerges that the high-quality water effluents resulting from scenarios 2, 3 and 4 are potentially suitable both for direct discharge into surface water body and for agricultural reuse. In contrast, the medium/low quality effluents from scenarios 1 and 2 present some parameters that are borderline or very close to the regulatory limits.

3.4. Economic analysis

The analysis of capital and operational costs allows the assessment of both the efficiency and scalability of processes. More specifically, operational expenditures (OPEX) include all annual costs necessary to keep the process running, such as routine maintenance, chemical reagents and labor costs. A detailed comparison of OPEX among the different scenarios helps to assess their long-term economic sustainability. On the other hand, capital expenditures (CAPEX) represent the investment costs required for the purchase of equipment, installation and plant commissioning. The economic analysis was carried out using simulations performed by SuperPro Designer (version 9.5), complemented by data derived from the manual by Van Haandel and Van der Lubbe (2007) [62].

Operating costs were calculated by summing fixed and variable costs, reported in Table 5. The fixed costs include:

- Labor costs, for which a wage of 23 €/h was considered, representing the Italian gross average in the same sector [63];
- Equipment maintenance, which is estimated at 15 % of the total cost of installed equipment [62];
- Laboratory costs, which include the analysis required for monitoring the quality of the treated water and the operational conditions of the

Table 3

Comparison between the 4 scenarios from a performance perspective. *The discharge is permitted due to the compliance of the limits established in Table 3, Annex 5 of Legislative Decree 152/06 [55].

Parameter	Biological process	Membrane process combined with AOPs	HC process as a pretreatment	HC process as a post- treatment
Water quality	Treated water of low/medium quality	Depending on the output stream: MF retentate: low/medium quality water NF permeate: high quality water Treated NF concentrate: low/ medium quality water	Treated water of high quality	Treated water of high quality
Estimated annual energy consumption (kWh)	157,700	1,971,000	7,542,000	210,000
Uses of treated water	Suitable for safe discharge into receiving surface water bodies*. Possible reuse in the cleaning of equipment and containers	Depending on the outgoing stream: MF Retentate: discharge required into the sewer system, possible reuse in dyeing processes. NF Permeate: high-quality water, possible reuse in rinsing processes. Treated NF Concentrate: discharge required into the sewer system, possible reuse in cleaning equipment, containers, or floors.	Suitable for safe discharge into a receiving surface water body*. Possible reuse in the washing and rinsing of both fabrics and equipment	Suitable for safe discharge into a receiving surface water body*. Possible reuse in the washing and rinsing of both fabrics and equipment
Management complexity	Consolidated and traditional process (careful of sudden temperature changes, which may cause a decrease in efficiency in the biological oxidation tank).	Requires frequent maintenance. Special attention is needed for fouling phenomena and solids containing iron hydroxide precipitates	No special attention is required, except to prevent solids from interfering with the proper functioning of the Venturi tube HC operation studied at laboratory and pilot scale	No special attention is required, except to ensure that solids do not interfere with the proper functioning of the Venturi tube. HC operation studied at laboratory and pilot scale

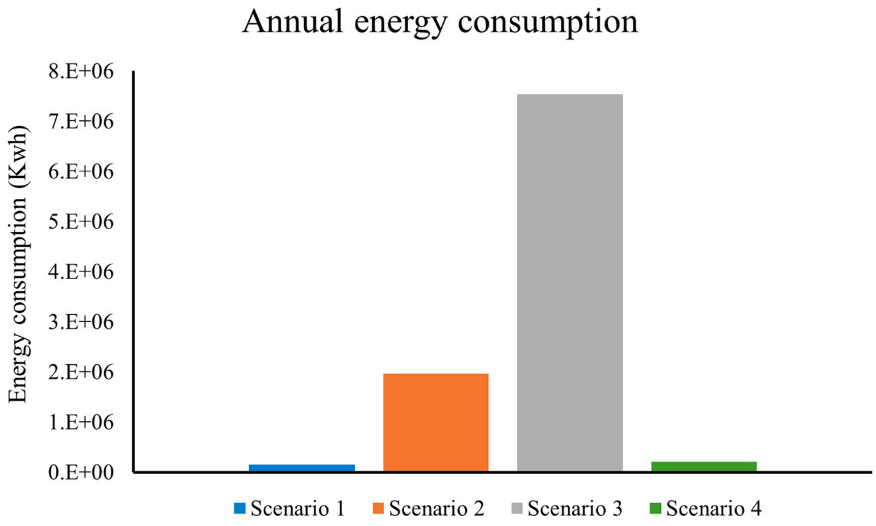

Fig. 5. Annual energy consumption of different scenarios.

plant, estimated at approximately 3 % of the total production costs [62].

The variable costs include:

- Solid waste disposal in authorized landfills, estimated at 0.12 €/kg [64];
- Utilities, primarily represented by the electricity required to operate, estimated at 0.30 €/kWh;
- Raw materials used in the process, for which prices information were obtained from the databases Intratec, Chemanalyst and IndexBox [65–67].

On the other hand, CAPEX was calculated by considering the equipment involved in each scenario (Fig. 1). Furthermore, to determine the CAPEX it was included working capital, such as the additional capital required to start up the plant, which was estimated at 10 % of the fixed capital investment. The CAPEX corresponds to the sum of fixed capital and working capital (Table 5).

The comparison of both OPEX and CAPEX of the different processes shows as scenario 1 is characterized by the lowest overall cost. Although this traditional approach is financially stable, it turns out to be less advantageous compared to the innovative alternatives offered by HC, as its inability to enable full reuse of the treated water limits its potential for cost savings. On the other hand, scenario 4 presents a more favorable balance between OPEX and CAPEX, making it a promising option for industrial scale-up. Scenario 3 also shows a reasonable balance between the two key economic parameters, although its operating costs are higher than those of scenario 4. This is primarily due to the higher energy demand and maintenance costs associated with the centrifuge. On the other hand, scenario 2 involves high expenditures in both CAPEX and OPEX, mainly due to the management of membrane modules and

Table 4
Comparison of final water quality of the present work against international standards.

Water use		BOD5	COD	TSS	Reference
Europe	Discharge	≤ 25 mg/L	≤ 125 mg/L	≤ 35 mg/L	[56]
	Reuse (agricolture)	≤ 10 mg/L	/	≤ 10 mg/L	[57]
USA	Discharge	≤ 30 mg/L	Not mandatory	≤ 30 mg/L	[58]
	Reuse (agricolture)	≤ 10 mg/L	/	≤ 10 mg/L	[59]
India	Discharge	≤ 30 mg/L	≤ 250 mg/L	≤ 100 mg/L	[60]
	Reuse (agricolture)	≤ 10 mg/L	≤ 50 mg/L	≤ 10 mg/L	[61]
Scenario 1	Medium low-quality water	3 mg/L	56 mg/L	4 mg/L	Present work
Scenario 2	Medium-low quality water	20 mg/L	286 mg/L	92 mg/L	Present work
	Medium-low quality water	19 mg/L	113 mg/L	0.6 mg/L	Present work
	High quality water	4 mg/L	32 mg/L	1 mg/L	Present work
Scenario 3	High quality water	3 mg/L	4 mg/L	0.8 mg/L	Present work
Scenario 4	High-quality water	3 mg/L	0.1 mg/L	3 mg/L	Present work

Table 5
Comparison of key economic parameters in the four studied processes.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
OPEX (€/years)				
Fixed costs				
Maintenance	49,000	180,000	110,000	84,000
Labor	130,000	210,000	270,000	280,000
Laboratory	8000	77,000	22,000	15,000
Variable costs				
Raw materials	2000	1,400,000	30,000	30,000
Solid waste treatment	18,000	17,000	73,000	19,000
Utilities	67,000	740,000	270,000	91,000
Total	274,000	2,600,000	780,000	520,000
CAPEX (€)				
Total	750,000	2,700,000	1,700,000	1,300,000

associated energy consumption, making it the least competitive option.

4. Conclusions

The textile sector is one of the most relevant and widespread industries globally, yet it is also among the most environmentally impactful, particularly concerning wastewater management. These effluents, characterized by chemical complexity and a high pollutant load, pose significant challenges to traditional treatment systems. Growing environmental awareness has driven research toward the development of technologies that not only reduce pollution but also promote water resource reuse, thereby fostering a circular economy.

In this regard, the present paper highlighted the great potential of HC as a wastewater treatment method, achieving a COD and BOD5 reduction of 98 %, and producing high-quality water suitable for reuse in new textile production processes. In addition to the scientific relevance of this result, further scale-up of this technique, supported by the economic assessments, should contribute to reducing the pressure on potable water resources, aligning with Sustainable Development Goal (SDG) 6 of the 2030 Agenda (ensure availability and sustainable management of water and sanitation for all). The application of LCA, chosen as a tool to define sustainable process design, demonstrated that implementing HC as a post-treatment following preliminary biological oxidation, combines technical gain with environmental benefits, reducing impacts in all considered categories, up to 90 % compared to HC as a pre-treatment (described in scenario 3). The fourth option also produces environmental benefit, compared to traditional biological approach (scenario 1) in key category such as Climate change, where the estimated impact saving is estimated at 30 %. The integration of technological development and LCA ensures the achievement of sustainability targets aligned with SDG 12 (ensure sustainable consumption and production patterns), with a particular focus on the climate change category. In this regard, the Monte Carlo analysis showed that implementing scenario 4, hypothesizing at least 50 % of energy produced by photovoltaic and the enhancement of resulting solid waste, can even generate carbon credits, which are crucial for addressing SDG 13 (Climate action).

CRediT authorship contribution statement

Valentina Innocenzi: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Alessia Amato:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Giulia Merli:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Marina Prisciandaro:** Resources, Project administration, Funding acquisition. **Karima Ayedi:** Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thank the Italian Ministry of University and Research Fund PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE – Bando 2022 – DD n. 104 del 02–02–2022 - Project: Sustainable Management strategies of liquid waste for transition to circular economy through hydrodynamic cavitation technology (HYDROCAVI-TECH) - ID project 2022CTFX9P, Missione 4 “Istruzione e Ricerca” Componente 2 “Dalla Ricerca all’Impresa”.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2025.118761.

Data Availability

Data will be made available on request.

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