AN OVERVIEW ON THE VIABLE METHODS FOR TEXTILE WASTEWATER TREATMENT

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ABSTRACT: *The textile industry is one of the major polluters of the environment, primarily due to the types and quantities of wastewater it produces. It is estimated that 20% of global water pollution is caused by textile processing, meaning that these processes generate enormous amounts of wastewater. Generally, this wastewater contains high levels of suspended solids, dyes, salts, pesticides, non-biodegradable organic substances, and heavy metals. The decline in water quality, along with increasingly stringent environmental protection regulations, has led the textile industry to turn to sustainable wastewater treatment methods that help reduce the global water footprint. This paper reviews some viable methods used for the treatment of wastewater originating from the textile industry. The focus is on advanced treatment techniques, such as adsorption, membrane-based filtration, electrochemical processes, and advanced oxidation. These methods offer potential solutions to mitigate the environmental impact of textile wastewater and promote sustainable water management practices.*

Keywords: *textile wastewater, sustainable technologies, advanced oxidation, membrane filtration, electrocoagulation.*

PREGLED ODRŽIVIH METODA PREČIŠĆAVANJA OTPADNE VODE TEKSTILNE INDUSTRIJE

APSTRACT: *Industrija tekstila je jedan od glavnih zagađivača životne sredine, prvenstveno zbog vrsta i količina otpadnih voda koje stvara. Procenjuje se da je 20% globalnog zagađenja vode potiče od proizvodnje tekstila. Generalno, ove otpadne vode sadrže visok sadržaj suspendovanih čvrstih materija, boja, soli, pesticida, nebiodegradabilnih organskih supstanci i teških metala. Pogoršanje kvaliteta vode, zajedno sa sve strožijim propisima o zaštiti životne sredine, naveli su tekstilnu industriju da se okrene ka primeni održivih metoda prečišćavanja otpadnih voda koje pomažu u smanjenju globalnog vodenog otiska. Ovaj rad daje pregled nekih održivih metoda koje se koriste za prečišćavanje otpadnih voda koje potiču iz tekstilne industrije. Fokus je na savremenim tehnikama prečišćavanja, kao što su adsorpcija, elektrohemijski procesi, oksidacija i membranska filtracija. Ove metode nude potencijalna rešenja za ublažavanje uticaja tekstilnih otpadnih voda na životnu sredinu i promovišu održivu praksu upravljanja vodama.*

Ključne reči: *otpadne vode tekstilne industrije, održive tehnologije, ozoniranje, membranska filtracija, elektrokoagulacija.*

1. INTRODUCTION

One of the most critical worldwide challenges is meeting the rising demand for water, driven by the worldwide expansion of industry, which in turn affects environmental stability, ecosystem health, and long-term economic development [1,2]. The industrial sector accounts for a significant proportion of global water usage, and the textile industry, in particular, is notorious for generating wastewater laden with dyes and chemicals that are detrimental to aquatic environments and the organisms within them. Various stages of textile processing- like sizing, scouring, bleaching, dyeing, and finishing- consume substantial water, with about 100-200 liters needed to process 1 kg of textile product [3,4]. Also, textile processing generates multiple wastewater streams with unique properties based on materials, processes, and chemicals used. Around 60-90% of process water is used for rinsing and washing, which can be cleaned and recycled [5]. Contaminated water with dyes and other various chemicals can also be treated by different techniques to reclaim water and recover chemicals [6,7].

Historically, the primary goal of textile wastewater treatment was the safe disposal of wastewater. However, inadequate treatment and the subsequent release of chemically contaminated water have caused severe pollution of aquatic ecosystems, posing risks to both the environment and human health. Over the past few years, significant advancements have been made in textile wastewater treatment, shifting the focus towards sustainable practices [8-10]. This shift is driven by stringent global regulations mandating sustainable water management strategies, including water reuse [11]. Efficient treatment of textile

wastewater has become a priority for water experts and environmentalists, aiming to operate the textile industry sustainably and prevent environmental damage [12].
The first two stages of wastewater treatment- primary and secondary- have been well-established and standardized over the years [13]. The primary stage involves removing suspended solids and gritty materials, while the secondary stage focuses on reducing oxygen demand, chemicals, and pollutants' color. Beside these advancements, the considerable effort has been dedicated to enhancing the tertiary stage of wastewater treatment, which addresses the removal of any remaining contaminants after the primary and secondary treatments. To achieve the highest treatment efficiency, various tertiary treatment techniques have been proposed [14,15]. The following is an overview of treatment methods for wastewater originated from the textile industry including adsorption, electrochemical processes, advanced oxidation, and membrane-based filtration. The aim is to highlight the potential of these methods to improve the purification process, ensuring compliance with environmental standards. This approach could accelerate the shift towards more sustainable water management practices.

2. TREATMENT METHODS

The treatment of wastewater from textile industry generally involves three main stages: primary, secondary, and tertiary treatment. Each stage removes different impurities, resulting in cleaner water. Primary treatment removes suspended solids, floating debris, and gritty materials. Secondary treatment reduces oxygen demand, other chemicals, and color. Tertiary treatment eliminates any remaining contaminants after the primary and secondary stages. Synthetic dyes are stable and non-biodegradable, making them difficult to remove through physical, chemical, or biological methods. Significant effort has been devoted to developing advanced treatment methods that are effective, affordable, flexible, and user-friendly. However, many of these methods are costly, especially when dealing with large volumes of waste.

2.1 Adsorption

Adsorption methods show great promise for future industrial wastewater treatment due to their effectiveness in removing organic and mineral contaminants, simplicity, and low cost. This physical process involves soluble molecules, called adsorbates, being removed from a solution by attaching to the surface of a solid substrate, known as an adsorbent. Textile dye or heavy metal adsorption can occur through physical adsorption, driven by Van der Waals forces and hydrogen bonds, or through chemical adsorption, which involves a reaction or complex formation between the adsorbent and the adsorbate.
Biosorption, a specific type of adsorption, occurs on living or dead microbial cells, trapping the dye and pollutants within the microbial biomass without breaking the dye’s physical structure [16]. Common adsorbents include activated carbon, biochar, chitosan, clay, resins, and zeolite. Researchers are exploring low-cost adsorbents derived from agricultural waste and developing novel adsorbents for the simultaneous removal of heavy metals and organic dyes [17,18]. Nanoparticles, due to their large surface area and porosity, offer better effectiveness and faster removal rates than traditional adsorbents [19,20]. Metal

oxide composites have also shown greater adsorption effectiveness compared to single metal oxides [21].
Key factors influencing adsorption include particle diameter, adsorbate concentration, temperature, and pH. The process has gained significant interest for its high decolorization efficiency for wastewater containing various dyes. However, adsorption is time-consuming and the sludge byproduct can be challenging to manage. Despite these challenges, the potential for developing efficient, low-cost adsorbents and improving adsorption techniques continues to drive research in this area.

Adsorption on activated carbon

Activated carbon is a microporous, homogeneous material with a large specific surface area (1 g has a surface area of up to 500 m²). It is derived from bituminous coal, coconut shells, wood, and anthracite through thermal or chemical activation processes. While not effective in removing all contaminants, it has the ability to bind with substances in liquid, solid, and gaseous states. When treating wastewater from the textile industry with activated carbon, it effectively removes chlorophenols, chlorinated hydrocarbons, dyes (color), surfactants, and substances that cause unpleasant odors. It also significantly reduces contamination from metals (Cu, Hg, Pb) and disinfection byproducts.
Activated carbon is used in the form of powder (PAC- Powdered Activated Carbon) or granules (GAC- Granular Activated Carbon) with a diameter of 1.2-1.6 mm. The process takes place in adsorption columns with activated carbon, more commonly using GAC, which simultaneously filters the water and conducts adsorption. The wastewater flow can be either downward or upward, and it is possible to regenerate GAC (by washing with acids or alkalis, steam, organic solvents, or thermal treatment), with a loss of 10% of the adsorbent. This reduces the problems and costs associated with the disposal and management of contaminated adsorbent and lowers the cost of acquiring new adsorbent (by up to 50%) [22].

2.2 Membrane filtration

In the textile industry, membrane technology is highly versatile and useful. This approach is cost-effective and energy-efficient, requiring fewer chemicals and less equipment, which makes it possible to remove various dyes and contaminants from wastewater and allows for the significant reuse of water. There are different types of membrane filtration available (Figure 1). Generally, microfiltration and ultrafiltration alone are not very efficient for wastewater treatment, so they are often followed by nanofiltration and reverse osmosis to achieve better results [23].

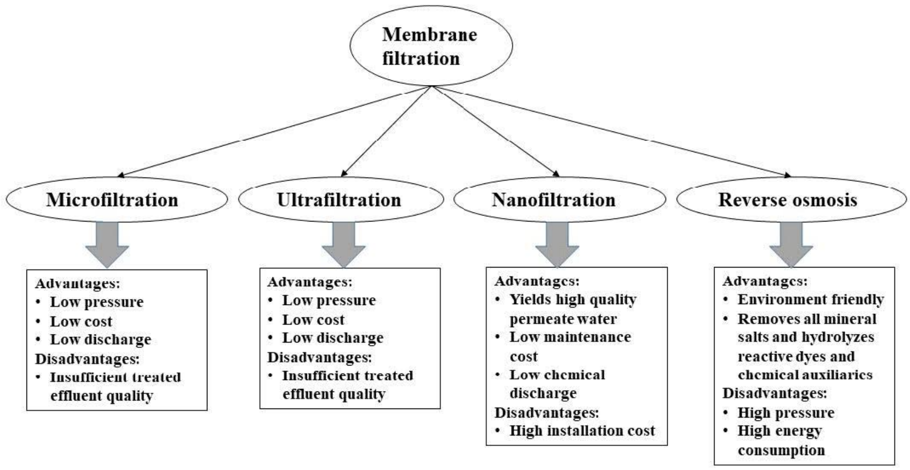

Figure 1: Types of membrane filtration with their advantages and disadvantages [23]

The basis of these operations is the membrane- a thin film (interface) that separates two phases and/or acts as an active or passive thin physical barrier to the transfer of substances between the two phases. This applies to semipermeable membranes and implies that there is a difference in chemical potential between the two phases.

The most common separation mechanisms, which depend on the specific properties of the components to be selectively removed or retained by the membrane, are:

a) Separation based on the difference in particle size and membrane pore size, known as the "sieve effect," through porous membranes that can have macropores larger than 50 nm and nanopores (mesopores) ranging from 2-50 nm. Processes dominated by this mechanism include microfiltration, ultrafiltration, nanofiltration, and dialysis.

b) Separation based on the difference in solubility and diffusivity of the membrane material and the solution in contact with the membrane, known as the solution/diffusion mechanism, using dense membranes in the following processes: gas permeation, pervaporation, and reverse osmosis.

c) Separation based on the difference in the charge of the particles to be separated (electrochemical effect) using ion-exchange (cationic or anionic) membranes. Processes dominated by this mechanism include electrodialysis, Donnan dialysis, and nanofiltration.

The membrane pore size defines the process. Table 1 shows the characteristics of membrane systems used in the textile industry.

Table 1: Characteristics of membrane processes used in the textile industry [22].

Process	Membrane pore size (µm)	Contaminants/ molar masses (g/mol)	Description
Microfiltration	0,007-2,00	Bacteria, suspended substances, pigments, oils, etc. >100000	Physical separation; particles with a size of 0.1-0.2 µm are removed, while particles larger than the pore size remain on the membrane
Ultrafiltration	0,002-0,10	Colloids, viruses, proteins, metal hydroxides, metals above 1 ppm, etc. 1000-200000	Best function is with a pressure gradient of 25 bar; Removal of particles either undissolved or suspended in water; retention of macromolecules and colloids; reduction of turbidity (99 %), COD and BOD.
Nanofiltration	0,001-0,07	Bacteria, viruses, dyes, pesticides, multivalent ions, etc. 180-15000	Performed at lower pressures than reverse osmosis, so it is cheaper; Discoloration and water hardness elements (Mg, Ca) removal.
Reverse osmosis	<0,001	Multivalent ions, viruses, bacteria, suspended substances, monovalent ions <200	Pressure is applied from the high-concentration solution side, membrane is permeable to water but impermeable to salt or contaminant molecules; High energy consumption because it requires a hydrostatic pressure gradient of 20–80 bar; high pollutant removal efficiency

According to their geometry, membranes are divided into flat and cylindrical, which can be tubular or in the form of hollow fibers.
According to their chemical nature, membranes are primarily polymers; they are made from modified natural and synthetic materials such as cellulose acetates, polyamide, polysulfone, acrylonitrile, polyethersulfone, teflon, nylon, polypropylene, and polycarbonate. Inorganic membranes are mainly ceramic, made from oxides, nitrides, and carbides of Al, Zr, and Ti, and are used for the separation of organic solvents that cannot be separated by polymeric membranes because they would dissolve.

2.3 Electrochemical processes

Electrochemical discoloration primarily targets the breakdown of reactive dyes, which constitute approximately 20–30% of the total market due to their vibrant and durable color properties. Generally, biological treatments are inadequate for effectively removing these dyes, physicochemical processes often leave behind residues that require further treatment, and absorbent materials need to be regenerated after multiple uses. Heavy metals are also successfully removed by electrochemical processes.

Electrocoagulation

Unlike chemical coagulation, electrocoagulation does not require the use of chemicals but has a better ability to remove pollutants. Electrocoagulation can remove a significantly broader range of pollutants than chemical coagulation, including heavy metals, suspended solids, bacteria, COD, BOD, pesticides, and herbicides. During electrocoagulation, substances are decomposed using electrical energy; direct current passes through metal electrodes, creating charged metal atoms that bind with dissolved contaminants and precipitate out of the solution [24].

Anode half-cell reaction: $M \rightarrow Mn^{+} + ne^{-}$
Cathode half-cell reaction: $2H_2O + 2e^{-} \rightarrow 2OH^{-} + H_2$
Formation of metal hydroxide: $Mn^{+} + nOH^{-} \rightarrow M(OH)_n$

The electrocoagulation process can be performed in batch or continuous modes. Batch processes are used in laboratory conditions, while continuous processes are ideal for industrial plants. In continuous processes, it is simpler to control operational parameters, making it easier to achieve better efficiency.
One of the drawbacks of this method is the need for frequent electrode replacement, as well as the formation of toxic organic compounds. Additionally, an impermeable oxide layer can form on the cathode, creating resistance to the flow of electric current, increasing power consumption, and consequently raising costs [22].
The advantages include the ability to treat large volumes of water at low cost, significantly less waste sludge generation compared to conventional coagulation, and much easier sludge treatment, drastically reducing disposal costs. The efficiency of electrocoagulation is over 95%, making it an excellent pretreatment for membrane technologies that require high-quality water for use.

2.4 Advanced oxidation processes

Advanced Oxidation Processes (AOPs) are an effective alternative to conventional methods, based on the production and utilization of highly reactive free radicals, particularly hydroxyl radicals capable of oxidizing and thus removing even non-biodegradable organic compounds present in wastewater. The most well-known and extensively researched AOPs include ozone oxidation (O_3), ozone oxidation with hydrogen peroxide (H_2O_2), ultraviolet radiation (UV), and the photo-Fenton process. They are often combined with ozonation at high pH values and the Fenton process. These processes are highly efficient in treating wastewater from the textile industry, especially in removing dyes and slowly biodegradable or non-biodegradable organic components.

Ozonation

Ozone dissolves well in water and can be effectively used for water disinfection. The limiting step in the ozonation process is the mass transfer of ozone from the gas phase to the liquid phase. The driving force and treatment efficiency of ozone vary and depend on the characteristics of the wastewater (pollutant concentration, pH value, etc.).

Ozonation is an eco-friendly wastewater treatment method since it does not create any harmful residues or chlorinated byproducts after oxidizing color, odor, and microorganisms. This process is typically performed in alkaline conditions (pH > 9) because the decomposition of ozone in water increases at higher pH levels. Ozone oxidizes inorganic and dissolved organic substances through two mechanisms [25]:

1. The direct reaction by ozone molecules, which is more selective and occurs slowly, is favored in acidic conditions.
2. The indirect reaction by free radicals, such as OH. and HOO., which is less selective and occurs more rapidly, is favored in basic conditions.

Therefore, the reaction pathway depends on the pH of the medium and the ozone dosage [26].

A simple method is used for introducing ozone into a reaction vessel containing wastewater, as shown in Figure 2 [27].

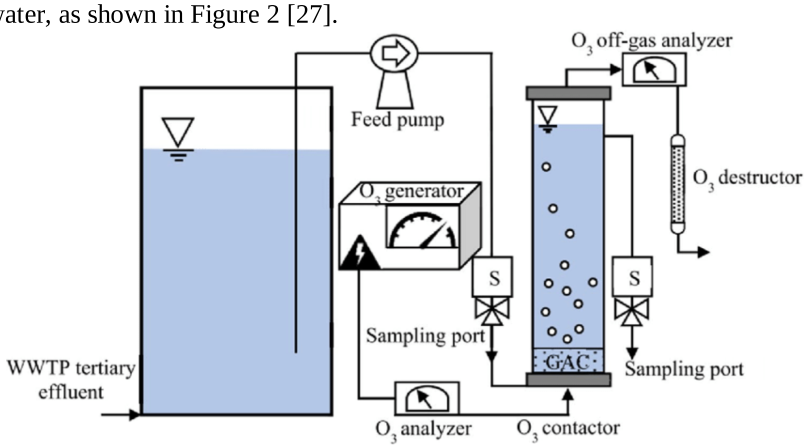

Figure 2: Water treatment by ozonation [27]

Ozone produced by corona discharge or UV radiation is introduced into the reactor with wastewater using a diffuser or turbine mixer. Better ozone treatment efficiency is achieved by optimizing process parameters such as temperature, pH value, and ozone dose [22]. Any remaining ozone that is not consumed in the process is destroyed using a thermal catalytic unit.

Ozone introduced into wastewater reduces the toxicity of textile dyes and enhances their biodegradability. By introducing ozone, the content of toxic substances in wastewater can be significantly reduced.

The advantages of ozonation include simplicity, elimination of conventional coagulation processes, removal of pesticides, organic compounds, reduction in BOD, COD, TOC, and organic load for secondary biological treatment.

Photocatalysis

Photocatalytic oxidation has a wide range of applications for degrading numerous organic and inorganic pollutants in wastewater.

The most widely adopted method for treating wastewater from textiles is the photocatalytic process, which offers the unique benefit of optical absorption not found in other Advanced Oxidation Processes (AOPs). Photocatalytic sensitization involves using a semiconductor as a catalyst to generate free radicals like $OH^{\bullet}$, which then oxidize organic compounds, converting them entirely into non-toxic substances such as CO_2 and H_2O through the absorption of photons. Figure 3 provides a schematic illustrating the basic mechanism of the photocatalytic oxidation process.

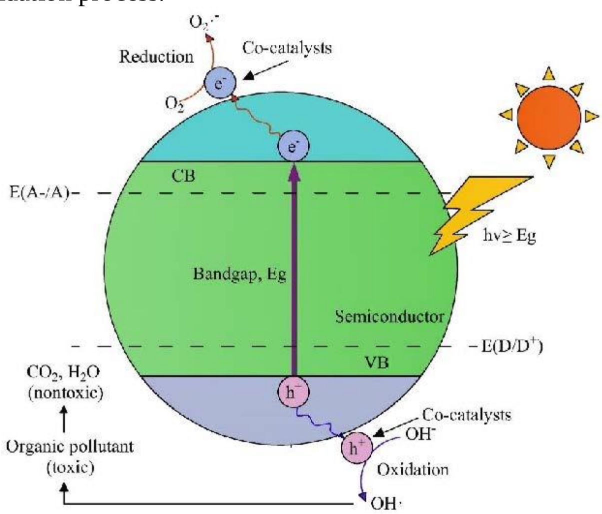

Figure 3: Scheme of the photocatalytic oxidation basic mechanism [28]

Many semiconductor oxides exhibit good photocatalytic activity. Among oxides with excellent photocatalytic activity, nano-TiO_2 stands out due to its advantages such as chemical and biological inertness, low cost, simple production and application, non-toxicity, and environmental acceptability. The photocatalytic properties of TiO_2 stem from the generation of photo-generated holes (h^+) and electrons (e^-) upon absorption of ultraviolet light matching its bandgap energy (E_{bg}). When the photocatalyst surface is irradiated with light energy equal to or greater than Ebg, electrons are excited from the valence to the conduction band, resulting in the formation of positive holes in the valence band. The produced electron-hole pairs (h^+e^-) can either recombine with heat release or migrate separately to the semiconductor surface where they can react with species adsorbed on the surface. Positive holes react with adsorbed water molecules, generating hydroxyl radicals ($OH^{\bullet}$). Holes and hydroxyl radicals oxidize organic molecules on the TiO_2 surface, while electrons reduce oxygen to form superoxide radical anions ($O_2^{\bullet-}$). When oxygen

reduction and pollutant oxidation processes do not occur simultaneously, electron accumulation in the conduction band leads to the recombination of electron-hole pairs, thereby reducing photocatalytic efficiency [29].
The most important elements for a successful photocatalytic system are the catalyst, light source, and reactor configuration. Since this process relies on light, the reactor or photocatalyst can be configured to utilize a readily available energy source, namely sunlight, to drive the reaction, thereby minimizing costs [30]. The type of radiation and placement of the light source in the reactor system are crucial for reactor design. In heterogeneous semiconductor photocatalysis, unlike traditional homogeneous processes, reactor design is more complex due to the presence of a solid photocatalyst. Photocatalysis is one of the most effective methods for dye removal, as well as reducing BOD and COD in wastewater from the textile industry.

3. CONCLUSION

In this paper, an integrated literature review of sustainable textile wastewater treatment methods and techniques has been presented. These innovative approaches aim to improve the purification process, ensuring that the treatment of wastewater from the textile industry meets the stringent standards required for environmental sustainability. By adopting these advanced methods, the textile industry can significantly reduce its environmental impact, contributing to the broader goal of viable water management. Additionally, policy frameworks and incentives are crucial to encourage the implementation of sustainable practices in textile wastewater management. The collective effort of industry stakeholders, researchers, and policymakers can continue driving the transformation towards a more sustainable and environmentally friendly textile industry.

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