OPTIMIZING TEXTILE EFFLUENTS TREATMENT: FROM CONVENTIONAL TO CUTTING-EDGE SOLUTIONS

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Abstract: *The textile industry is a significant global water consumer, generating wastewater laden with pollutants such as dyes, organic compounds, detergents, and heavy metals. The safe disposal and treatment of these effluents are critical to mitigating severe environmental threats, including pollution of water bodies and health risks to humans and aquatic life. This paper reviews various methods for treating textile wastewater, focusing on the ecological and regulatory demands for sustainable water management. Traditional treatment approaches, often insufficient, have driven the exploration of advanced and integrated wastewater treatment technologies. Key methods include physical, chemical, and biological treatments, alongside emerging techniques like membrane filtration, activated carbon adsorption, and advanced oxidation processes (AOPs). AOPs, particularly, offer high efficiency in removing non-biodegradable organic pollutants, making them a promising solution for the textile industry. This comprehensive review underscores the need for innovative, cost-effective, and eco-friendly treatment strategies to ensure sustainable operations and compliance with environmental standards.*

Keywords: wastewater treatment, textile industry, advanced oxidation processes, membrane filtration, activated carbon adsorption, environmental sustainability.

OPTIMIZACIJA TRETMANA TEKSTILNIH OTPADNIH VODA: OD KONVENCIONALNIH DO INOVATIVNIH REŠENJA

Apstrakt: *Tekstilna industrija je značajan globalni potrošač vode, koji generiše otpadne vode bogate zagađivačima kao što su boje, organska jedinjenja, deterdženti i teški metali. Bezbedno odlaganje i tretman ovih otpadnih voda su ključni za ublažavanje ozbiljnih ekoloških pretnji, uključujući zagađenje vodenih tela i zdravstvene rizike za ljude i akvatične organizme. Ovaj rad daje pregled različitih metoda tretmana otpadnih voda* *iz tekstilne industrije, sa posebnim osvrtom na ekološke i regulativne zahteve za održivo upravljanje vodama. Tradicionalni pristupi, često nedovoljni, podstakli su istraživanje naprednih i integrisanih tehnologija prečišćavanja otpadnih voda. Najvažnije metode podrazumevaju fizičke, hemijske i biološke, uz napredne tehnike kao što su membranska filtracija, adsorpcija aktivnim ugljem i napredni oksidacioni procesi. Naročito napredni oksidacioni procesi nude visoku efikasnost u uklanjanju nebiorazgradivih organskih zagađivača, što ih čini obećavajućim rešenjem za tekstilnu industriju. Ovaj sveobuhvatni pregled naglašava potrebu za inovativnim, isplativim i ekološki prihvatljivim strategijama tretmana kako bi se osigurale održive operacije i usklađenost sa ekološkim standardima.*

Ključne reči: tretman otpadnih voda, tekstilna industrija, napredni oksidacioni procesi, membranska filtracija, adsorpcija aktivnim ugljem, ekološka održivost.

1. INTRODUCTION

The textile industry is one of the largest water-consuming industries globally, generating wastewater containing pollutants such as dyes, degradable organics, detergents, and heavy metals. 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 is one of the most critical worldwide challenges. The release of textile effluents poses serious environmental threats, including pollution of water bodies, endangering human health and socioeconomic life of people, aquatic life, and plants due to the presence of carcinogenic, mutagenic, genotoxic, cytotoxic, and allergenic pollutants. Ecological standards are gaining importance in every step of the textile unit, emphasizing the need for an eco-friendly model to overcome flaws and adhere to environmental standards [1-4]. Different stages of textile processing, such as sizing, scouring, bleaching, dyeing, and finishing, consume substantial amounts of water, requiring approximately 100-200 liters to process 1 kg of textile product [5,6]. Additionally, these processes generate multiple wastewater streams with unique properties depending on the materials, processes, and chemicals used. About 60-90% of the process water is utilized for rinsing and washing, which can be treated and recycled [7]. Contaminated water containing dyes and various chemicals can also be treated using different techniques to reclaim water and recover chemicals [8,9].

Historically, the primary aim of textile wastewater treatment was the safe disposal of wastewater. However, inadequate treatment and the subsequent discharge of chemically contaminated water have resulted in severe pollution of aquatic ecosystems, posing significant risks to both the environment and human health.

Efforts to address these pollutants include the development of eco-friendly and cost-effective treatment methods. The complex characteristics of textile wastewater, including high color, high biological oxygen demand/ chemical oxygen demand (BOD/COD), and salt load, present challenges for effective treatment [1,10]. Conventional treatment methods may have limitations in efficiently removing pollutants from textile effluents, leading to the need for multistep treatments and the exploration of innovative and emerging techniques [11,12]. Various treatment processes such as physical, chemical, biological, combined, and other technologies are being explored to remove these pollutants from textile wastewater. Advanced treatment technologies such as membrane technology, activated carbon method, and advanced oxidation processes (AOPs) have shown promise in effectively removing pollutants from textile wastewater. Advanced oxidation processes (AOPs) have been identified as effective techniques for treating textile pollutants due to their cost-effectiveness, high performance, and lower consumption of materials and reagents [13].

The textile industry is focusing on sustainable wastewater treatment methods to reduce water footprint and operational costs, aligning with the recent shift towards environmentally friendly practices in business [14]. This shift is motivated by strict global regulations that require sustainable water management strategies, such as water reuse [15]. Consequently, efficient treatment of textile wastewater has become a top priority for water experts and environmentalists, who aim to ensure the textile industry operates sustainably and mitigates environmental harm [16]. The selection of wastewater treatment modes significanly influences treatment cost and effectiveness, playing a crucial role in the sustainable development of the textile industry [17].

The treatment of wastewater from the textile industry generally involves three main stages: primary, secondary, and tertiary treatment. Each stage removes different impurities, resulting in progressively cleaner water. The primary stage focuses on removing suspended solids, floating debris, and gritty materials. The secondary stage aims to reduce oxygen demand, chemicals, and the color of pollutants. Tertiary treatment targets the elimination of any remaining contaminants after the primary and secondary stages.

Synthetic dyes are stable and non-biodegradable, which makes them challenging to remove through conventional physical, chemical, or biological methods. The primary and secondary stages of wastewater treatment have been well-established and standardized over the years [18]. Despite these advancements, considerable effort has been dedicated to enhancing the tertiary stage of wastewater treatment, which focuses on removing any remaining contaminants after the initial treatments. Various tertiary treatment techniques have been proposed to achieve the highest treatment efficiency [19,20].

Significant effort has been devoted to developing advanced treatment methods that are effective, affordable, flexible, and user-friendly. However, many of these methods can be costly, especially when dealing with large volumes of waste. The following is an overview of treatment methods for wastewater from the textile industry. The aim is to highlight the potential of these methods to improve the purification process and ensure compliance with environmental standards. This approach could accelerate the shift towards more sustainable water management practices.

2. TREATMENT METHODS FOR TEXTILE WASTEWATER

Selecting the appropriate method for treating textile wastewater depends on various factors, including the production process, the chemicals used, and the composition of the wastewater. Other important considerations include discharge regulations, location, business and operational costs, land availability, and the potential for reusing or recycling treated water. It's crucial to ensure that treated water, especially if intended for drinking, is colorless and free of toxic compounds to avoid additional treatment costs.

Wastewater from cotton dyeing industries is particularly polluted, with high levels of color, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and total solids due to the presence of dyes and other chemicals. The color in the wastewater can interfere with photosynthetic activity and the development of aquatic organisms, leading to environmental imbalance. To address these issues, various treatment methods have been developed, including physical, chemical, and biological processes. Often, a combination of these methods is used to effectively and economically treat textile wastewater before it is discharged into rivers [21-23].

2.1. Physical treatment methods

Physical treatment methods remove substances from wastewater by using natural forces such as electrical attraction, gravity, and van der Waals forces, or by employing physical barriers. These methods do not alter the chemical structure of the substances in the water. Occasionally, the physical state of these substances may change, or dispersed substances may coagulate [24].

2.1.1 Adsorption

Adsorption methods hold significant promise for future industrial wastewater treatment due to their effectiveness in removing organic and mineral contaminants, simplicity, and low cost. This process involves the removal of soluble molecules (adsorbates) from a solution by attaching them to the surface of a solid substrate (adsorbent). Adsorption of textile dyes or heavy metals can occur through physical adsorption, driven by Van der Waals forces and hydrogen bonds, or through chemical adsorption, involving reactions or complex formations between the adsorbent and the adsorbate.

Biosorption is a specific type of adsorption that occurs on living or dead microbial cells, trapping dyes and pollutants within the microbial biomass without breaking the dye's physical structure [25]. Common adsorbents include activated carbon, biochar, chitosan, clay, resins, and zeolite. Researchers are also exploring low-cost adsorbents based on different waste materials such as those derived from agricultural waste for the simultaneous removal of heavy metals and organic dyes [26,27] as well as waste cotton and cotton/polyester yarns combined with fly ash from thermal power plant for heavy metals removal [28]. Nanoparticles, with their large surface area and porosity, offer better effectiveness and faster removal rates than traditional adsorbents [29,30]. Metal oxide composites have also shown greater adsorption effectiveness compared to single metal oxides [31].

Several key factors influence the adsorption process, including particle diameter, adsorbate concentration, temperature, and pH. Adsorption has gained significant interest for its high efficiency in decolorizing wastewater containing various dyes. However, it is a time-consuming process, and managing the sludge byproduct can be challenging. Despite these challenges, ongoing research is focused on developing efficient, low-cost adsorbents and improving adsorption techniques to enhance the overall process.

Adsorption on activated carbon

Activated carbon is a microporous, homogeneous material characterized by a large specific surface area, where 1 g can have a surface area of up to 500 m^2. It is produced from bituminous coal, coconut shells, wood, and anthracite through thermal or chemical activation processes. Although it is not effective in removing all contaminants, activated carbon excels at binding with substances in liquid, solid, and gaseous states.

When treating wastewater from the textile industry, activated carbon is particularly effective at removing chlorophenols, chlorinated hydrocarbons, dyes (color), surfactants, and substances that cause unpleasant odors. Additionally, it significantly reduces contamination from metals such as copper (Cu), mercury (Hg), and lead (Pb), as well as disinfection byproducts.

Mechanism of dye adsorption on activated carbon during textile wastewater treatment is schematically presented in Figure 1 [32].

Activated carbon is available in two primary forms: powdered (PAC - Powdered Activated Carbon) and granular (GAC - Granular Activated Carbon) with a diameter of 1.2-1.6 mm. The treatment process typically occurs in adsorption columns packed with activated carbon, usually utilizing GAC, which simultaneously filters the water and conducts adsorption. The flow of wastewater through the columns can be either downward or upward.

One of the advantages of using GAC is that it can be regenerated, which involves washing with acids or alkalis, steam, organic solvents, or thermal treatment. This regeneration process can result in a 10% loss of the adsorbent, but it significantly reduces the problems and costs associated with the disposal and management of contaminated adsorbent. Furthermore, it lowers the cost of acquiring new adsorbent by up to 50% [33].

2.1.2 Membrane filtration

In the textile industry, membrane technology proves to be highly versatile and practical. This approach is both cost-effective and energy-efficient, requiring fewer chemicals and less equipment. These factors contribute to its effectiveness in removing various dyes and contaminants from wastewater, enabling significant water reuse.

The core component of these operations is the membrane, a thin film that acts as an interface separating two phases and serves as either an active or passive physical barrier to the transfer of substances between these phases. This separation process involves semipermeable membranes, which rely on a difference in chemical potential between the two phases. The size of the membrane pores is crucial in defining the separation process.

Membranes are primarily composed of polymers, which can be derived from modified natural and synthetic materials such as cellulose acetates, polyamide,

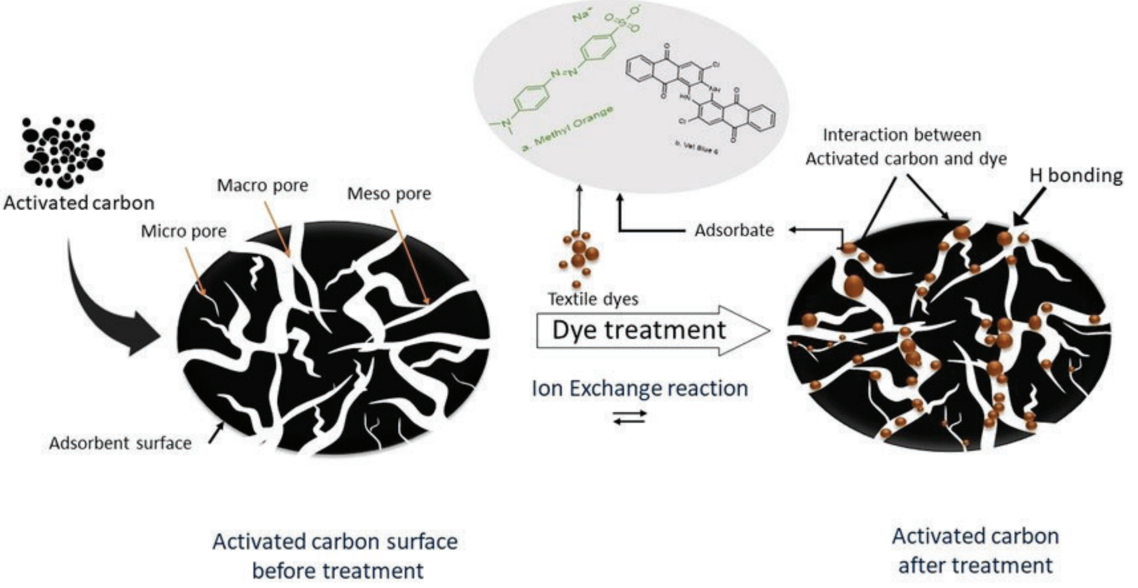

Figure 1: Mechanism of textile dye adsorption on activated carbon [32]

polysulfone, acrylonitrile, polyethersulfone, Teflon, nylon, polypropylene, and polycarbonate. Inorganic membranes are typically ceramic and are made from oxides, nitrides, and carbides of metals like aluminum (Al), zirconium (Zr), and titanium (Ti). These ceramic membranes are used for separating organic solvents, a task that polymeric membranes cannot perform as they would dissolve in the process. Based on their geometry, membranes are categorized as either flat or cylindrical, with the latter being further divided into tubular forms or hollow fibers.

There are several types of membrane filtration available, as illustrated in Figure 2. Generally, microfiltration and ultrafiltration alone do not efficiently treat wastewater. Therefore, these processes are often followed by nanofiltration and reverse osmosis to achieve superior results.

Microfiltration

Microfiltration membranes feature pores that range in size from 0.1 to 10 μm, evenly distributed across the membrane. This technology primarily works through a sieving process to separate macromolecules, colloids, and suspended particles from solutions. It is frequently employed in various filtration applications but has limited effectiveness in treating textile wastewater due to its similarity to traditional filtration methods.

In textile wastewater treatment, microfiltration is often used to process dye baths containing dye pigments, with pore sizes around 0.1–1 μm. Additionally, it serves as a pretreatment step before processes like reverse osmosis or nanofiltration [34].

Ultrafiltration

Ultrafiltration (UF) membranes typically have pore diameters between 2 and 10 nm and operate best under a pressure gradient of around 25 bar. UF is commonly used to remove undissolved or suspended particles and to retain macromolecules and colloids in water. These membranes are usually made from synthetic polymers such as polyvinyl chloride (PVC), polyamides (PA), and polyacrylonitrile (PAN).

In textile wastewater treatment, UF membranes can struggle to effectively filter dye molecules that are smaller than the membrane pores. While enhanced UF methods with aggregation have been explored for dye removal, they are not widespread. UF can separate macromolecules and particles sized between 1 nm and 0.05 μm but does not effectively remove dissolved pollutants like dyes, limiting its ability to prepare water for sensitive applications such as textile fabric dyeing [35]. UF is often combined with biological reactors or used as a pretreatment for reverse osmosis.

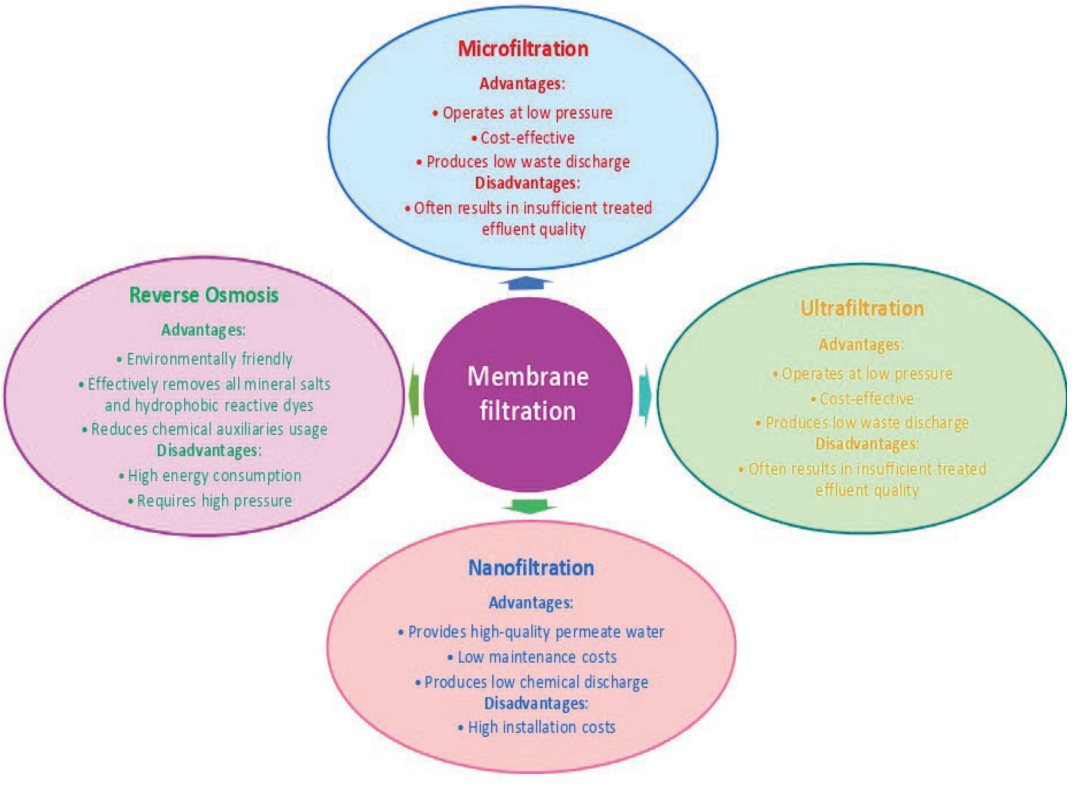

Figure 2: Types of membrane filtration with their advantages and disadvantages

Nanofiltration

Nanofiltration (NF) is a highly promising method for treating textile effluent. NF membranes have an average pore size of around 1 nm and operate under pressures of 5–35 bars. They effectively filter small organic molecules and ions sized between 10^{-9} and 10^{-8} m. NF membranes are particularly effective at rejecting divalent and trivalent ions due to the formal charges on the NF membrane polymers.

Nanofiltration stands out because it requires minimal maintenance, has low discharge volumes, high solvent permeability, scalability, and produces high-quality water suitable for reuse. However, operational challenges such as fouling and salt breakdown can complicate its use, especially in the presence of salts. NF is typically used after biological treatment or ultrafiltration and sometimes before reverse osmosis to enhance performance [36,37].

In textile effluent treatment, NF handles solutions of nanometer-sized particles with retention weights of about 80–1000 da. A combination of adsorption and nanofiltration can be used to manage polarization concentration during filtration processes. NF membranes effectively retain low molecular weight divalent ions, large monovalent ions, hydrolyzed reactive dyes, and other dyeing auxiliaries. This method is an efficient and environmentally favorable solution for treating complex and highly concentrated textile effluents.

Reverse Osmosis

Reverse osmosis (RO) involves membranes that are permeable to water but impermeable to salt or contaminant molecules. By applying pressure to the high-concentration side, water is forced through the semipermeable membrane to the low-concentration side, leaving pollutants behind. Although it is an environmentally friendly method with high removal efficiency, RO requires a significant hydrostatic pressure gradient (20–80 bar), leading to high energy consumption. Given the high conductivity of textile wastewater, RO is often necessary for effective water recovery [38].

RO can decolorize and remove chemical compounds from dye house wastewater in a single step, achieving retention rates of 90% or higher for most ionic compounds. This process excludes all mineral salts, hydrolyzed reactive dyes, and chemical compounds. The osmotic pressure needed for separation correlates directly with the concentration of dissolved salts, affecting the energy required.

2.2. Chemical treatment methods

During wastewater treatment, various chemicals are used to speed up the disinfection process. These chemical methods, known as chemical unit processes, involve a range of chemical reactions and are often used in combination with physical and biological processes. Common chemical treatment methods include coagulation, flocculation, chemical precipitation, chemical oxidation, and advanced oxidation processes (AOPs). Techniques such as electrochemical treatments and Fenton oxidation are also frequently employed to treat textile wastewater [24].

2.2.1 Conventional chemical methods

The coagulation/flocculation (CF) process is widely used for dye removal from wastewater, particularly in the textile industry, due to its cost-efficiency and ease of operation. This method is commonly employed to destabilize particles or colloids, making it an effective approach for purifying residual dye baths. For example, it is used to treat wastewater from a cotton/polyamide blend dyed black. The process relies on the addition of coagulants, which associate with pollutants to form coagulates or flocks. These then precipitate and are removed by flotation, settling, filtration, or other physical technologies, ultimately forming sludge that requires further treatment to reduce its toxicity [39,40]. The schematic presentation of the coagulation/flocculation process is given in Figure 3.

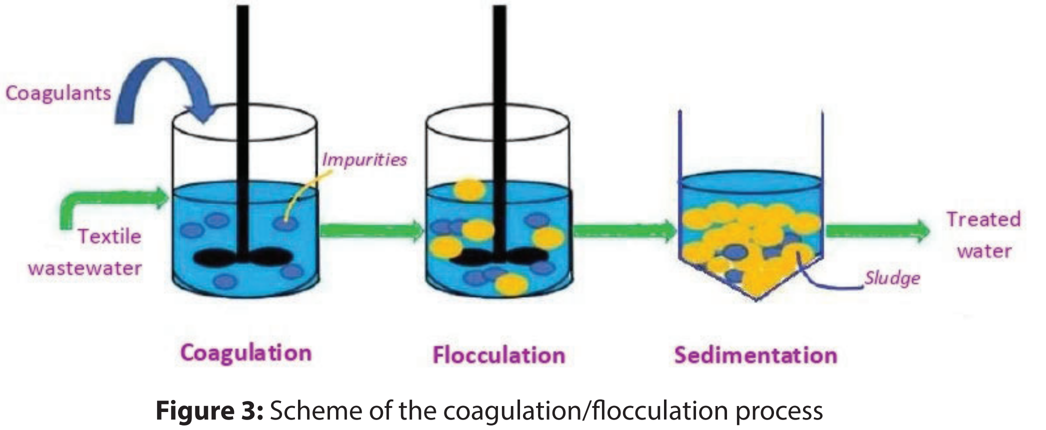

Figure 3: Scheme of the coagulation/flocculation process

Various coagulants play critical roles in the CF process, including inorganic coagulants such as iron and aluminum salts, which are widely used in textile wastewater treatment [41,42]. However, the use of these conventional coagulants poses environmental and health risks, prompting the search for safer alternatives. Environmentally friendly substances, such as chitosan, Moringa oleifera seeds, tannins, and Jatropha curcas seeds, are being increasingly studied as viable options [43].

In addition to dye removal, the CF process is effective in reducing Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), and color from effluents. However, the method has its drawbacks, particularly the high cost associated with treating the resulting sludge and the restrictions on its disposal into the environment. Despite these challenges, CF remains a widely adopted method for treating textile wastewater, with ongoing research focused on improving its efficiency and sustainability.

2.2.2 Electrochemical processes

Electrochemical processes are highly effective in wastewater treatment, particularly for the discoloration and breakdown of reactive dyes. These dyes, known for their vibrant and durable color properties, account for approximately 20-30% of the total dye market. Reactive dyes are challenging to remove because traditional biological treatments are often inadequate, and physicochemical processes tend to leave behind residues that need additional treatment. Additionally, absorbent materials used in these processes require regeneration after several uses. The efficiency of electrochemical treatments in handling reactive dyes is significant because these dyes are not only resistant to biodegradation but also pose environmental risks due to their stable chemical structures. The electrochemical approach addresses these challenges by decomposing the dyes into non-toxic substances. Moreover, the versatility of electrochemical processes allows for the simultaneous removal of various contaminants, including heavy metals, which are common in industrial wastewater.

One of the main advantages of electrochemical processes is their ability to achieve high removal efficiencies without the need for extensive chemical additives. This reduces the secondary pollution often associated with chemical coagulation and other traditional methods. Additionally, electrochemical systems can be designed for continuous operation, making them suitable for industrial-scale applications.

Electrocoagulation

Unlike chemical coagulation, electrocoagulation does not rely on chemicals and is more effective at removing a wide variety of pollutants. This method can eliminate heavy metals, suspended solids, bacteria, COD, BOD, pesticides, and herbicides more efficiently than chemical coagulation. Electrocoagulation works by using electrical energy to break down substances; a direct current is passed through metal electrodes, generating charged metal atoms that bind with dissolved contaminants, causing them to precipitate out of the solution [44].

The reactions in the electrocoagulation process can be summarized as follows:

Anode half-cell reaction:

$$M \rightarrow M^{n+} + ne^-$$

Cathode half-cell reaction:

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2$$

Formation of metal hydroxide:

$$M^{n+} + nOH^- \rightarrow M(OH)_n$$

Electrocoagulation can be carried out in either batch or continuous modes. Batch processes are typically used in laboratory settings, while continuous processes are better suited for industrial applications due to easier control over operational parameters, which enhances efficiency.

However, this method has some drawbacks, such as the frequent need to replace electrodes and the potential formation of toxic organic compounds. Additionally, an impermeable oxide layer can form on the cathode, creating resistance to the electric current, increasing power consumption, and raising operational costs [33].

Despite these challenges, electrocoagulation offers significant advantages, including the capability to treat large volumes of water at a low cost, reduced waste sludge generation compared to traditional coagulation, and simpler sludge treatment, which lowers disposal costs. With an efficiency rate of over 95%, electrocoagulation is an excellent pretreatment step for membrane technologies that require high-quality water.

2.2.3 Advanced oxidation processes

Advanced Oxidation Processes (AOPs) offer a highly effective alternative to traditional wastewater treatment methods. These processes rely on the generation and use of highly reactive free radicals, especially hydroxyl radicals, which can oxidize and remove even the most stubborn, non-biodegradable organic compounds found in wastewater. The most prominent and widely studied AOPs include ozone oxidation (O_3), ozone oxidation combined with hydrogen peroxide (H_2O_2), ultraviolet (UV) radiation, and the photo-Fenton process. These methods are often used in conjunction with high pH ozonation and the Fenton process to enhance their effectiveness.

AOPs are particularly efficient in treating wastewater from the textile industry, where they excel at removing dyes and organic components that are either slowly biodegradable or entirely non-biodegradable. For example, ozonation at high pH values allows for rapid decolorization of textile wastewater, while the combination of UV radiation and hydrogen peroxide enhances the degradation of persistent pollutants. The photo-Fenton process, which uses a combination of ferrous sulfate and hydrogen peroxide in the presence of UV light, enables high efficiency in the oxidation of organic compounds and reduction of chemical oxygen demand (COD).

Additional potential of AOPs lies in their ability to integrate with other treatment methods to achieve even higher levels of efficiency. For instance, after applying AOPs, the treated water can be further processed using membrane technologies or biological processes to achieve complete elimination of pollutants and allow for water reuse. In this way, advanced oxidation processes not only improve the quality of wastewater but also contribute to sustainable water resource management in the textile industry.

Ozonation

Ozonation is a highly effective method for treating textile wastewater due to ozone's excellent solubility in water and its potent disinfection capabilities. One of the key challenges in the ozonation process is the mass transfer of ozone from the gas phase to the liquid phase, which can influence the overall efficiency of the treatment. The effectiveness of ozone treatment is highly dependent on the characteristics of the wastewater, including pollutant concentration and pH value.

The scheme of the ozonation process iz given in Figure 4 [11].

Ozonation is an environmentally friendly treatment method as it does not produce harmful residues or chlorinated byproducts after oxidizing color, odor, and microorganisms. Typically, this process is performed under alkaline conditions (pH > 9) because ozone decomposes more rapidly at higher pH levels, enhancing its effectiveness. Ozone oxidizes inorganic

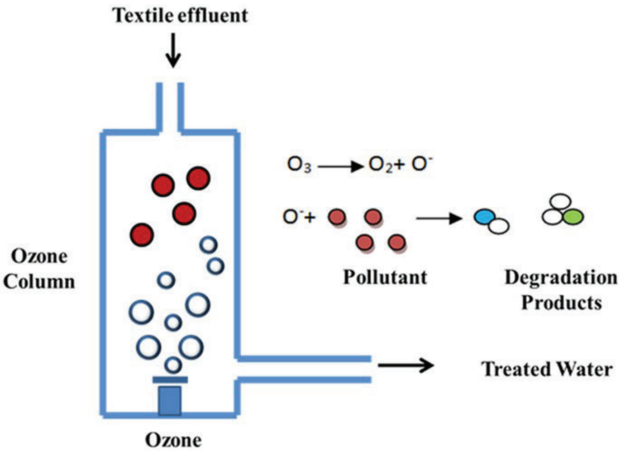

Figure 4: Scheme of the ozonation process [11]

and dissolved organic substances through two primary mechanisms [45]:

1. Direct reaction by ozone molecules- This reaction is more selective, occurs slowly and is favored in acidic conditions.
2. Indirect reaction by free radicals (e.g., OH• and HOO•)- This reaction is less selective but occurs more rapidly, and is favored in basic conditions.

Therefore, the reaction pathway and overall efficiency of ozonation depend on the medium's pH and the ozone dosage used [46].

Ozone is typically produced by corona discharge or UV radiation and introduced into the wastewater reactor using a diffuser or turbine mixer. Optimizing process parameters such as temperature, pH value, and ozone dose can significantly enhance treatment efficiency [33]. Any remaining ozone that is not consumed in the process is safely destroyed using a thermal catalytic unit.

The introduction of ozone into wastewater not only reduces the toxicity of textile dyes but also enhances their biodegradability. This leads to a significant reduction in the content of toxic substances in the wastewater.

Advantages of ozonation include its simplicity, the elimination of conventional coagulation processes, and its ability to remove pesticides and organic compounds. Additionally, ozonation effectively reduces BOD, COD, TOC, and the organic load for secondary biological treatment, making it an integral part of advanced wastewater management. Furthermore, ozonation can be integrated with other treatment processes to achieve comprehensive purification, ensuring that the treated water meets environmental safety standards.

Photocatalysis

Photocatalytic oxidation is highly effective for degrading a variety of organic and inorganic pollutants in wastewater. It is particularly popular in the textile industry due to its unique benefit of optical absorption, a feature not found in other Advanced Oxidation Processes (AOPs). This process involves using a semiconductor as a catalyst to generate free radicals, like hydroxyl radicals (OH•), which oxidize organic compounds and convert them into non-toxic substances such as carbon dioxide (CO_2) and water (H_2O) through photon absorption. The basic mechanism of this process is illustrated in Figure 5 [47].

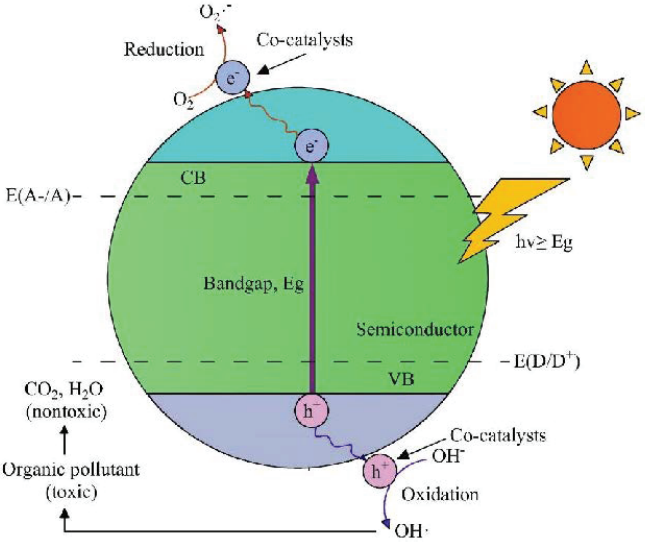

Figure 5: Scheme of the photocatalytic oxidation basic mechanism [47]

Several semiconductor oxides display significant photocatalytic activity, with nano-TiO_2 standing out due to its numerous advantages, including chemical and biological inertness, low cost, ease of production and application, non-toxicity, and environmental acceptability. TiO_2's photocatalytic properties are due to the generation of photo-generated holes (h^+) and electrons (e^-) when ultraviolet light is absorbed at an energy level matching its bandgap energy (E_{bg}). When the surface of TiO_2 is irradiated with light energy equal to or greater than its E_{bg}, electrons are excited from the valence band to the conduction band, creating positive holes in the valence band. These electron-hole pairs (h^+e^-) can either recombine, releasing heat, or migrate separately to the semiconductor surface where they react with adsorbed species. Positive holes react with water molecules to produce hydroxyl radicals (OH•). These holes and radicals oxidize organic molecules on the TiO_2 surface, while electrons reduce oxygen to form superoxide radical anions (O_2•⁻). If oxygen reduction and pollutant oxidation do not occur simultaneously, electron accumulation in the conduction band leads to recombination of electron-hole pairs, reducing the efficiency of photocatalysis [48].

A successful photocatalytic system relies on the catalyst, light source, and reactor configuration. Given that this process depends on light, the reactor or photocatalyst can be designed to use sunlight, which is a readily available energy source, to drive the reaction and reduce costs [49]. The type of radiation and the placement of the light source within the reactor system are critical for effective reactor design. In heterogeneous semiconductor photocatalysis, the design is more complex than in traditional homogeneous processes due to the presence of a solid photocatalyst. Despite this complexity, photocatalysis is among the most effective methods for removing dyes and reducing Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) in wastewater from the textile industry.

2.3. Biological treatment methods

Biological degradation of dyes is an environmentally friendly technique for removing dyes from textile wastewater. This method is cost-effective and can be performed under optimal conditions with minimal operational costs. Ali recommends using biomaterials such as algae, bacteria, fungi, and yeasts, which can decompose and absorb various synthetic dyes, to achieve effective biological degradation.

Biological treatment methods are particularly effective and environmentally sustainable for handling textile wastewater. These methods utilize bacteria to remove dyes from wastewater through discoloration processes that occur under both anaerobic and aerobic conditions. Compared to clariflocculator treatment methods, biological approaches are more efficient in removing dissolved materials by mimicking natural self-purification processes [22,50].

The efficiency of biological treatments depends on the ratio of organic load to biomass in oxidation ponds, as well as the temperature and oxygen concentration. Aeration increases biomass concentration in the oxidation pond but must be controlled to prevent disrupting the biomass. Biological treatment processes are divided into aerobic and anaerobic methods, with aerobic treatment being the most widely used due to its high efficiency and broad applications.

2.3.1 Sequencing batch reactor activated sludge process

In a Sequential Batch Reactor (SBR), a discontinuous biological wastewater treatment process occurs using activated sludge. This represents a modification of the activated sludge process (ASP), the usually applied aerobic method that removes both the dissolved organic solids and the suspended solids. The activated sludge contains heterotrophic microorganisms, with bacteria playing the most crucial role, comprising about 95% of the total biomass. Besides breaking down organic and inorganic pollutants in the water, some bacteria can secrete extracellular sticky polymeric substances (polysaccharides and/or polypeptides), which enable the formation of activated sludge flocs, where degradation occurs both on the surface and within the flocs. The process primarily involves aerobic oxidation reactions of organic pollutants and anaerobic denitrification. To maintain the necessary oxygen concentration for oxidation, as well as for the exchange of substrates and metabolites, aeration of the activated sludge suspension and wastewater is required. The prerequisite for the denitrification process, which is the reduction of nitrites and nitrates to atmospheric nitrogen, is the lack of oxygen; thus, the process in the SBR involves alternating aerobic and anaerobic conditions. The procedure consists of filling the reactor, carrying out aerobic and anaerobic reactions, sedimentation, decanting or discharging treated water, and removing excess activated sludge from the reactor. After sedimentation, the purified water is discharged, and the sludge remains stored at the bottom of the basin. Excess sludge is removed using pumps or an air lift during the resting phase. After resting, the tank is refilled with wastewater, and a new cycle begins. In an SBR-based treatment plant, processes are carried out in a single volume within specified time periods for the various previously mentioned cycles. Oxygen supply is provided by an aeration system, and bacteria oxidize organic substances as in conventional activated sludge plants, but only during part of the treatment [24].

Shematic presentation of the operation of the SBR, consisting of six phases: 1. water inflow (filling the reactor), 2. mixing, 3. aeration, 4. sedimentation and decanting, 5. discharge of treated water and removal of excess activated sludge, and 6. resting, is given in Figure 6.

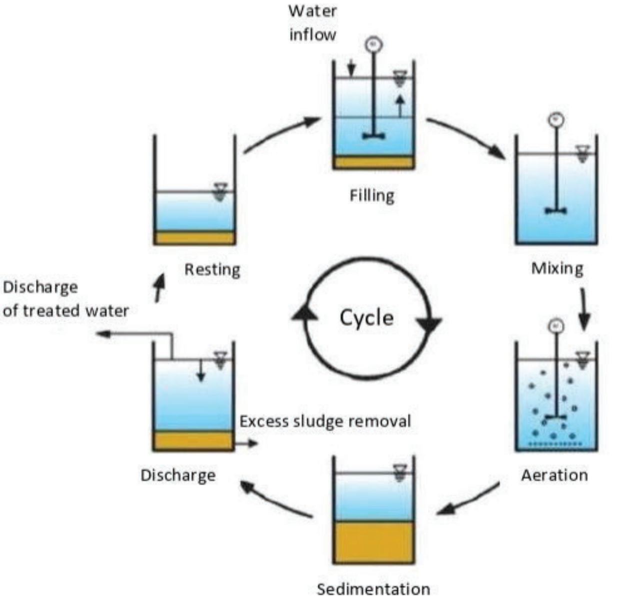

Figure 6: SBR operating cycle

The advantages of the SBR process lie in its effective control and flexibility in handling a variety of pollutants, allowing compliance with increasingly stringent regulations regarding wastewater discharge. The main disadvantage is the slow rate of microbial degradation, resulting in a treatment duration of up to 30 hours [33].

2.3.2 Membrane Bioreactor

A Membrane Bioreactor (MBR) is a combination of a conventional biological wastewater treatment system (bioreactor) with activated sludge and a membrane filtration unit (microfiltration and ultrafiltration). By incorporating the membrane component into the reactor, the need for a separate secondary clarifier and additional filtration of the wastewater is eliminated. Figure 7 illustrates the wastewater treatment process in MBR in a traditional activated sludge system compared to MBR technology [51].

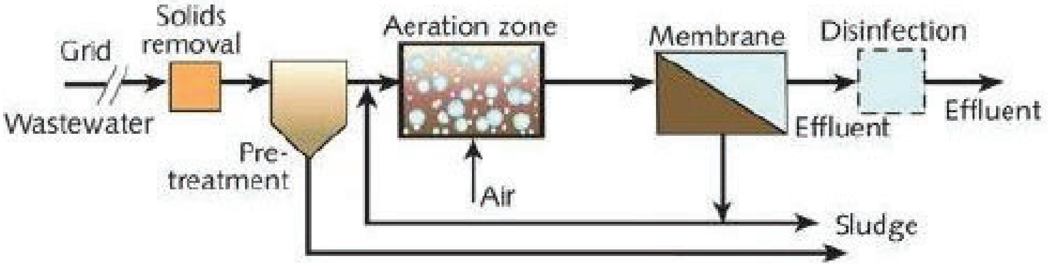

Figure 7: Wastewater treatment in MBR [51]

By aerating the water and maintaining an optimal concentration of activated sludge for the growth of microorganisms for 10-15 days in the bioreactor basin, a sufficient number of microorganisms are established, which can efficiently treat all the present organic matter in the wastewater within a short period. The concentration of activated sludge ranges from 8.0 to 12.0 g of dry matter per liter, compared to 2.0 to 3.0 g of dry matter per liter in conventional systems. The higher biomass concentration ensures better removal of dissolved and suspended biodegradable substances from wastewater with increased organic content. Extended retention time of activated sludge (more than 15 days) also facilitates the nitrification process, even during cold weather.

After biological treatment, the water passes through membranes that retain microorganisms and residual organic and inorganic substances while allowing high-purity water to pass through. The cleaning of the separation system – microfiltration membranes – is performed through backwashing at short intervals.

The use of membrane bioreactors is on the rise and will continue to be employed wherever high-quality effluents are required, whether due to sensitive natural receivers or for water reuse as process water. The increasing efficiency of MBR technology, along with the growing interest in water for both industrial (reuse and recycling technology) and human consumption, indicates a bright future for this method [51,52].

3. CONCLUSION

The treatment of wastewater from the textile industry presents significant challenges due to the complex and variable nature of the effluents, which often contain high levels of color, BOD/COD, and salt load. Untreated textile wastewater can lead to severe environmental pollution, adversely affecting aquatic life, ecosystems, and human health due to the presence of dyes, heavy metals, and other hazardous substances. This review has highlighted several effective treatment methods. Conventional treatment methods have limitations in effectively removing all pollutants, necessitating the use of multistep treatments and the exploration of innovative and emerging techniques. The 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. Future research should focus on optimizing these treatment technologies to enhance pollutant removal efficiency and develop sustainable water management practices. Emphasis should be placed on economically viable and environmentally friendly methods, including zero liquid discharge and resource recovery, to align with the global shift towards sustainable practices.

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REFERENCES

[1] Siddique, K., Rizwan, M., Shahid, M.J., Ali, S., Ahmad, R., Rizvi, H. (2017). Textile wastewater treatment options: A critical review, *Enhancing Cleanup of Environmental Pollutants*, 2, 183–207.

[2] Tomar, S., Shahadat, M., Ali, S.W., Joshi, M., Butola, B.S. (2022). Treatment of Textile-Wastewater Using Green Technologies, In: *Green Chemistry for Sustainable Water Purification* (UI-Islam S., Shalla A.H., Shahadat M., eds.), 129-156, Wiley- Scrivener Publishing.

[3] Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn S.E., Sullivan C.A., Liermann C.R., et al. (2010). Global threats to human water security and river biodiversity, *Nature*, 467, 555-561.

[4] Grant, S.B., Saphores, J.-D., Feldman, D.L., Hamilton, A.J., Fletcher, T.D., Cook, P.L.M., Stewardson, M., Sanders, B.F., Levin, L.A., Ambrose, R.F., et al. (2012). Taking the "Waste" Out of "Wastewater" for Human Water Security and Ecosystem Sustainability, *Science*, 337, 681-686.

[5] Holkar, C.R., Jadhav, A.J., Pinjari, D.V., Mahamuni, N.M., Pandit, A.B. (2016). A critical review on textile wastewater treatments: Possible approaches, *Journal of Environmental Management*, Vol. 182, 351-366.

[6] Hussain, T., Wahab, A. (2018). A critical review of the current water conservation practices in textile wet processing, *Journal of Cleaner Production*, 198, 806-819.

[7] Yaseen, D.A., Scholz, M. (2018). Treatment of synthetic textile wastewater containing dye mixtures with microcosms, *Environmental Science and Pollution Research*, 25, 1980-1997.

[8] Lin, J., Ye, W., Huang, J., Ricard, B., Baltaru, M.-C., Greydanus, B., Balta, S., Shen, J., Vlad, M., Sotto, A., et al. (2015). Toward Resource Recovery from Textile Wastewater: Dye Extraction, Water and Base/Acid Regeneration Using a Hybrid NF-BMED Process, *ACS Sustainable Chemistry and Engineering*, 3, 1993-2001.

[9] Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J.A., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V., Ruokolainen, J. (2021). Wastewater Treatment and Reuse: A Review of its Applications and Health Implications, *Water, Air and Soil Pollution*, 232, e208.

[10] Astuti, A.D., Muda, K. (2018). Biosorption Processof Synthetic Textile Waste-water using Bjerkandera Agusta via Response Surface Methodology (RSM), *1st SRICOENV 2018*, E3S Web of Conferences, 68, 04020.

[11] Kallawar, G.A., Bhanvase, B.A. (2024). A review on existing and emerging approaches for textile wastewater treatments: challenges and future perspectives, *Environmental science and pollution research international*, 31(2), 1748-1789.

[12] Choudhury, A.K.R. (2021). 5 - Technologies for the management of wastewater generated in wet processing, In: *The Textile Institute Book Series*, *Waste Management in the Fashion and Textile Industries* (Nayak R., Patnaik A., eds.), 99-129, Woodhead Publishing.

[13] Rahimi, M.R., Mosleh, S. (2018). Intensification of textile wastewater treatment processes, In: Advanced Textile Engineering Materials (Ul-Islam S., Butola B.S., eds.), 329-387, Scrivener, Salem.

[14] Sachidhanandham, A., Periyasamy, A.P. (2021). Environmentally Friendly Wastewater Treatment Methods for the Textile Industry, In: *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications,* 1-4 (Kharissova O. V., Torres-Martínez L. M., Kharisov B. I., eds.), 2269-2307, Springer International Publishing.

[15] Voulvoulis, N. (2018). Water reuse from a circular economy perspective and potential risks from an unregulated approach, *Current Opinion in Environmental Science and Health*, 2, 32-45.

[16] Agarwal, S., Singh A.P. (2022). Performance evaluation of textile wastewater treatment techniques using sustainability index: An integrated fuzzy approach of assessment, *Journal of Cleaner Production*, Vol. 337, e130384.

[17] Ma, Y., Wang, J., Li, Y. (2017). Study on improvement for wastewater treatment mode in textile industry, *Journal of Silk*, 54(4), e 41107.

[18]Lofrano G., Brown J. (2010). Wastewater management through the ages: A history of mankind, *Science of the Total Environment*, Vol. 408, 5254-5264.

[19] Wang, X., Jiang, J., Gao, W. (2022). Reviewing textile wastewater produced by industries: Characteristics, environmental impacts, and treatment strategies, *Water Science and Technology*, Vol. 85, 2076-2096.

[20] Ibrahim, Y., Banat, F., Naddeo, V., Hasan, S.W. (2019). Numerical modeling of an integrated OMBR-NF hybrid system for simultaneous wastewater reclamation and brine management, *Euro-Mediterranean Journal for Environmental Integration*, 4, e23.

[21] Ketin, S., Andrejić, M., Čabarkapa, O., Biočanin, R. (2023). Wastewaters originated from the textile industry, *Tekstilna industrija*, 71(3), 47-51.

[22] Holkar, C. R., Jadhav, A. J., Pinjari, D. V., Mahamuni, N. M., Pandit, A. B. (2016). A critical review on textile wastewater treatments: possible approaches, *Journal of Environmental Management*, 182, 351-366.

[23] Younas, T., Tayyaba, N., Ayub, A., Ali, S. (2021). Textile fabrics and dyes, *Tekstilna industrija*, 69(3), 47-51.

[24] Mani, S., Chowdhary, P., Bharagava, R. N. (2019). Textile wastewater dyes: toxicity profile and treatment approaches, In: *Emerging and Eco-Friendly Approaches for Waste Management* (Bharagava R. N., Chowdhary P., eds.), 219-244, Springer, Singapore.

[25] Ali, H. (2010). Biodegradation of Synthetic Dyes- A Review, *Water, Air, and Soil Pollution*, 213, 251-273.

[26] Afroze, S., Sen, T.K. (2018). A Review on Heavy Metal Ions and Dye Adsorption from Water by Agricultural Solid Waste Adsorbents, *Water, Air, and Soil Pollution*, 229, e225.

[27] Hossain, M.Y., Zhu, W., Pervez, M.N., Yang, X., Sarker, S., Hassan, M.M., Hoque, M.I.U., Naddeo, V., Cai, Y. (2021). Adsorption, kinetics, and thermodynamic studies of cacao husk extracts in waterless sustainable dyeing of cotton fabric, *Cellulose*, 28, 2521-2536.

[28] Trivunac, K., Vukčević, M., Maletić, M., Karić, N., Pejić, B., Perić Grujić, A. (2023). Waste materials as adsorbents for heavy metals removal from water: comparative analysis of modification techniques, *Tekstilna industrija,* 70(1), 4-10.

[29] Othman, N.H., Alias, N.H., Shahruddin, M.Z., Abu, Bakar, N.F., Nik, Him N.R., Lau, W.J. (2018). Adsorption kinetics of methylene blue dyes onto magnetic graphene oxide, *Journal of Environmental Chemical Engineering*, 6, 2803-2811.

[30] Sakil, M., Nahid, P.M., Faridul, H.K.M., Abu, T.M., Hui-Hong, L. (2019). In situ synthesis of green AgNPs on ramie fabric with functional and catalytic properties, *Emerging Materials Research*, Vol. 8, 623-633.

[31] Xia, M., Chen, Z., Li, Y., Li, C., Ahmad, N.M., Cheema, W.A., Zhu, S. (2019). Removal of Hg(II) in aqueous solutions through physical and chemical adsorption principles, *RSC Advances*, 9, 20941-20953.

[32] Lotha, T.N., Sorhie, V., Bharali,,P., Jamir, L. (2024). Advancement in Sustainable Wastewater Treatment: A Multifaceted Approach to Textile Dye Re-

moval through Physical, Biological and Chemical Techniques, *Chemistry Select*, 9, No. 11, e202304093.

[33] Periyasamy, A.P. et al. (2018). *Sustainable Innovations in Apparel Production*, In: *Textile Science and Clothing Technology* (Muthu S.S., ed.), Springer Nature Singapore Pte Ltd.

[34] El Harfi, A. (2017). Remediation of dyes in textile effluent by membrane based treatment techniques: A critical review, *Maghrebian Journal of Pure and Applied Science*, 3, 1-8.

[35] Van der Bruggen B., Vandecasteele C., Van Gestel T., Doyen W., Leysen R. (2003). A review of pressure-driven membrane processes in wastewater treatment and drinking water production, *Environmental Progress*, Vol. 22, 46–56.

[36] Pervez, M.N., Mishu, M.R., Stylios, G.K., Hasan, S.W., Zhao, Y., Cai, Y., Zarra, T., Belgiorno, V., Naddeo, V. (2021). Sustainable Treatment of Food Industry Wastewater Using Membrane Technology: A Short Review, *Water*, 13, e3450.

[37] *Sustainable Membrane Technology for Water and Wastewater Treatment*, (Figoli A., Criscuoli A., eds.), Book Series: Green Chemistry and Sustainable Technology (2017), Springer, Singapore.

[38] Cui, ZF., Jiang Y., Field R.W. (2010). Fundamentals of pressure-driven membrane separation processes. In: Membrane Technology; Elsevier: Amsterdam, The Netherlands; 1–18.

[39] Huang, X., Bo, X., Zhao, Y., Gao, B., Wang Y., Sun S., Yue Q., Li Q. (2014). Effects of compound bioflocculant on coagulation performance and floc properties for dye removal, *Bioresource Technology*, 165, 116-121.

[40] Golob, V., Vinder, A., Simonic, M. (2005). Efficiency of the coagulation/flocculation method for the treatment of dyebath effluents, *Dyes and Pigments*, 67, 93-97.

[41] Abbas, M. J., Mohamed, R., Al-Sahari, M., Al-Gheethi, A., Mat Daud, A. M. (2021). Optimizing $FeCl_3$ in coagulation-flocculation treatment of dye wastes, *Songklanakarin Journal of Science & Technology*, 43, 1094-1102.

[42] Jalal, G., Abbas, N., Deeba, F., Butt, T., Jilal, S., Sarfraz, S. (2021). Efficient removal of dyes in textile effluents using aluminum-based coagulant, *Chemistry International*, 7, 197-207.

[43] Hameed, Y. T., Idris, A., Hussain, S. A., Abdullah, N., Man, H.C., Suja, F. (2018). A tannin–based agent for coagulation and flocculation of municipal wastewater as a pretreatment for biofilm process, *Journal of Cleaner Production*, 182, 198-205.

[44] Barrera-Díaz, C.E., Balderas-Hernández, P., Bilyeu, B. (2018). Electrocoagulation: Fundamentals and Prospectives, In: *Electrochemical Water and Wastewater Treatment*, (Martínez-Huitle C.A., Rodrigo M.A., Scialdone O., Eds.) 61–76, Butterworth-Heinemann, Oxford, UK.

[45] Sevimli, M.F., Sarikaya, H.Z. (2002). Ozone treatment of textile effluents and dyes: Effect of applied ozone dose, pH and dye concentration, *Journal of Chemical Technology and Biotechnology*, 77, 842-850.

[46] Shriram, B., Kanmani, S. (2014). Ozonation of textile dyeing wastewater- A review, *Journal of Institue of Public Health Engineers*, Vol. 2014-15, No. 3, 46-50.

[47] Chen, Y.-d., Duan, X., Zhou, X., Wang, R., Wang, S., Ren, N., Ho, S.-H. (2021). Advanced oxidation processes for water disinfection: Features, mechanisms and prospects, *Chemical Engineering Journal*, Vol. 409, e128207.

[48] Turchi, C.S., Ollis, D.F. (1990). Photocatalytic degradation of organic water contaminants: Mechanisms involving hydroxyl radical attack, *Journal of Catalysis*, 122, 178-192.

[49] Staehelin, J., Hoigne, J. (1982). Decomposition of ozone in water: Rate of initiation by hydroxide ions and hydrogen peroxide, *Environmental Science and Technology*, 16, 676–681.

[50] Das, A., Mishra, S. (2017). Removal of textile dye reactive green-19 using bacterial consortium: process optimization using response surface methodology and kinetics study, *Journal of Environmental Chemical Engineering*, 5, 612-627.

[51] Pandey, A., Singh, R.K., Industrial Waste Water Treatment by Membrane Bioreactor System, *Elixir Chemical Engineering*, 70, 23772-23777.

[52] Jegatheesan, V., Pramanik, B. K., Chen, J., Navaratna, D., Chang, C.-Y., Shu, L. (2016). Treatment of textile wastewater with membrane bioreactor: a critical review, *Bioresource Technology*, 204, 202-212.

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