Korean J. Chem. Eng., 40(9), 2060-2081 (2023)
DOI: 10.1007/s11814-023-1475-2

pISSN: 0256-1115
eISSN: 1975-7220

REVIEW PAPER

Wastewater from the textile industry: Review of the technologies for wastewater treatment and reuse

Ali Ahsan*, Farrukh Jamil*,†, Moeen Ali Rashad*, Murid Hussain*,†, Abrar Inayat, Parveen Akhter***, Ala'a H. Al-Muhtaseb****, Kun-Yi Andrew Lin*****, and YoungKwon Park******,†**

*Department of Chemical Engineering, COMSATS University Islamabad, Lahore Campus, Defence Road,
Off Raiwind Road, Lahore, Pakistan
**Department of Sustainable and Renewable Energy Engineering, University of Sharjah, 27272, Sharjah, United Arab Emirates
***Department of Chemistry, The University of Lahore, Defence Road, Off Raiwind Road, Lahore, Pakistan
****Department of Petroleum and Chemical Engineering, Sultan Qaboos University, Muscat, Oman
*****Department of Environmental Engineering, National Chung Hsing University, 250 Kuo-Kuang Road, Taichung, Taiwan
******School of Environmental Engineering, University of Seoul, Seoul 02504, Korea

(*Received 9 February 2023 • Revised 8 April 2023 • Accepted 17 April 2023*)

Abstract−The textile industry is water intensive and discharges numerous coloring compounds into the water body that depend on the industry's geographical location, the wet processes used for manufacturing, processing conditions, and the substrates involved. Textile wastewater contains chlorobenzenes, phthalates, heavy metals, azo dyes, and chlorophenols that have severe health issues, such as being allergenic, cytotoxic, genotoxic, mutagenic, and carcinogenic threats to living organisms. The differing concentrations of sulfates, chlorides, TOC, TDS, TSS, BOD, COD, high pH, and dye content characterize textile wastewater. To protect the environment and public health, a higher concentration of these items in textile wastewater is needed to treat the textile wastewater effluent before discharge. The conventional treatment methods are not able to fully remove the pollutants, such as physical treatments can only remove grease, oil, and TSS, whereas biological wastewater treatment (aerobic and anaerobic) can only decrease colors, COD, BOD, oil, and phenol with a higher accomplishment period and by-products. Therefore, it is necessary to develop effective eco-friendly, cost-effective, novel techniques, such as membrane technology, and a promising method with fewer by-products. The activated carbon method effectively removes heavy metals and dyes from the textile wastewater, and advanced oxidation processes (AOPs) are a recent development in textile wastewater treatment processes. Combining AOPs methods has been proven effective in removing pollutants when combined with biological and advanced physical processes. This paper reviews the textile manufacturing process, textile wastewater characteristics, textile wastewater's impact on the environment and health, and the available textile wastewater treatment approach.

Keywords: Textile Wastewater, Textile Pollutants, Health & Environmental Concerns, Wastewater Treatment

INTRODUCTION

Water resources are being depleted with the growth of industries, socio-economy, and population, creating the need for waste water to be treated for reuse or disposal [1]. According to Boretti and Rosa [2], by the end of 2050, the world's population will reach 9.4 to 10.2 billion, which will strain the clean water system. The waste water from industries, agriculture and municipalities is an issue that needs to be countered for the sustainability of water resources, as 70% of the total water supply is consumed by agriculture, 21% by industries and 9% by households [3]. Out of the 21% of water used in industries, 79 billion cubic meters is used in the textile industry globally, which will be increased by 50% by the end of 2030 [4]. The textile industry is the second highest to produce wastewater that is causing severe environmental problems, specifically, the wet process of the textile industry has major contribution to it [4,5]. The textile industry uses chemicals that go to the effluent and cause water pollution. Different methods are present for textile wastewater treatment, but these textile chemicals are hard to treat as they require a combination of multiple processes to reuse or treat the effluent water.

Three types of textile industries depend on the production of fabrics; the textile industries producing mohair, silk and wool are characterized as protein fabric-producing textiles. The second category comes under the synthetic fiber-producing factories that produce synthetic fiber artificially; the typical fibers produced in these factories are acrylic, polyester and nylon, while linen, rayon and cotton are produced in the factories that use cellulosic material [5,6]. The fiber produced in these factories involves wet and dry processes. In contrast, wet processes are considered the most wastewater-releasing, including a high percentage of contamination. Fig. 1 demonstrates the wet process and different pollutants released in textile wastewater [7].

[†] To whom correspondence should be addressed.
E-mail: fjamil@cuilahore.edu.pk, drmhussain@cuilahore.edu.pk,
ykpark0426@gmail.com

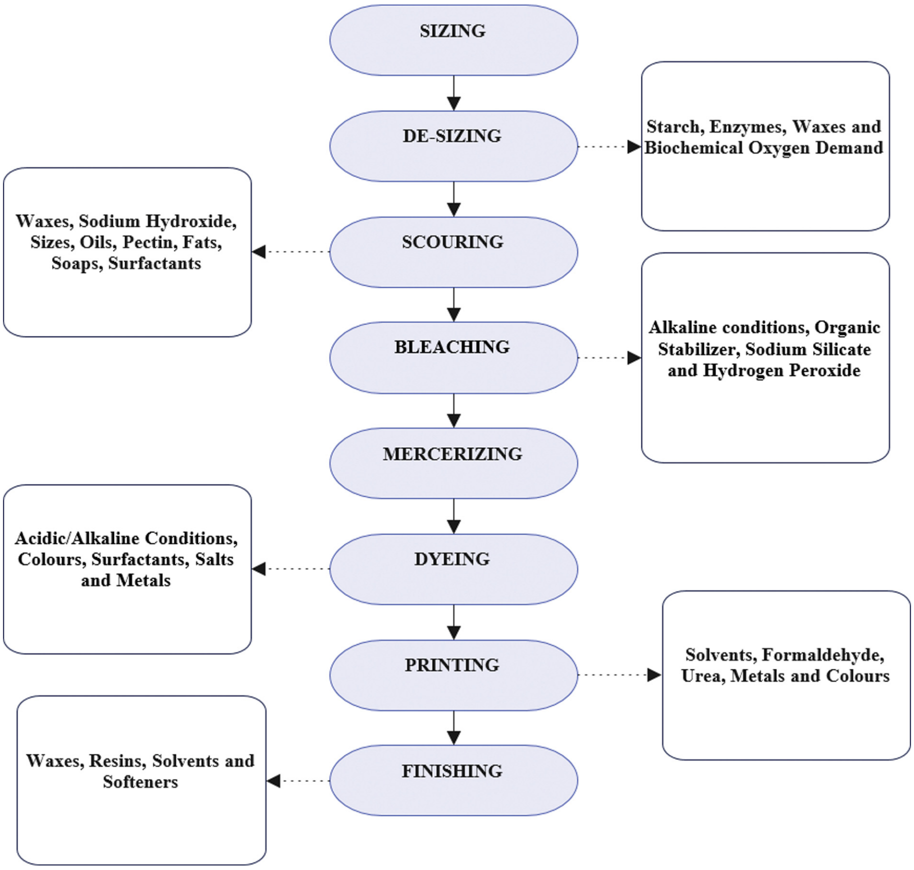


Fig. 1. Wet processes of textile industries and different pollutants released from textile wastewater.

These steps of the wet process have an intense water requirement, and it is the primary source of water contamination as its effluents contaminate the surface water, sediment and soil [8]. Therefore, flowing wastewater causes water and environmental pollution by dispersing agents, surfactants, salts, dyes, colors, metal ions, bases, acids and other chemicals with clean water resources [9]. Water consumption in the textile industry is greater than in any other industry. It has become the most potable water-consuming industry, as 200 L/kg of potable water is consumed to produce one textile product [7]. Wang et al. [10] reported that the dyeing and finishing steps generate around 17-20% industrial wastewater. According to the World Health Organization report, 20 million hectares of land are irrigated with untreated textile wastewater worldwide [11]. It is also worth mentioning that up to 80% of untreated textile wastewater is used to irrigate vegetables in countries like Pakistan and their locals experienced health problems [12]. Some chemicals in wastewater require high operation costs to remove from wastewater, such as chemicals used for the dyeing process. The chemical used in dyes has heterocyclic and aromatic structures and color-display groups that are stable, hard to remove and decompose [13]. In developing countries, many textile industries release highly contaminated wastewater into the clean water streams due to the time and cost associated with treatment operations. Also, the clean water resources are being depleted as the textile is utilizing water from clean water resources and simultaneously discharging the contaminated water into the clean water.

The textile industry is the largest water-consuming industry, generating a larger volume of contaminated wastewater, posing severe health and environmental problems. The untreated hazardous textile wastewater makes the need to develop efficient, cost-effective and sustainable wastewater treatment options. Although there is growing research in the field of textile wastewater treatment, it lacks rigorous and systematic analysis of treatment options and the environmental impacts of this polluted wastewater. Sikiru et al. [14] reviewed membrane technologies, Sarayu and Sandhya [15], Dikshit [16], and Mishra et al. [17] reviewed the biological textile wastewater treatment, and Pa'zdzior and Bilinska [18], and Hassan and Carr [19] reviewed advance oxidation processes. Limited reviews, such as Kishor et al. [20] presented all technological advancements in textile wastewater treatment. So, this review can provide a critical and comprehensive evaluation of existing literature, informing policymakers and industries on the decision-making processes and identifying research gaps in textile wastewater for future studies.

This review discusses the impact of textile wastewater on the environment and human beings, then explores the processes and methods, such as physical, biological, and chemical treatment. The aim is to review the various treatment methods of treating textile wastewater with their advantages and disadvantages by comparing the different operational parameters and their removal efficiencies. The review includes the recent advancement in the advanced oxidation process, activated carbon process, and membrane technology. This study also includes extensive literature on combined technologies that are the emerging technologies in textile wastewater treatments.

OVERVIEW OF TEXTILE MANUFACTURING PROCESSES AND WASTEWATER COMPOSITION

1. Profile of the Textile Industry

The textile industry is a major key player in the world economy, but at the same time, it is causing pollution. The market share value of the textile industry is $2,000 billion, and it is expected that the textile sector will contribute $266.38 billion in employment worldwide in 2025. The textile sector employs workers without having special skills that make it attractive for people to work in this sector in developed and developing countries such as Pakistan, India, Nigeria, Mauritius, Sri Lanka, Vietnam, Bangladesh, etc. The textile industries are classified based on technology and raw material used in the processes. Based on the raw material used in the processes, the textile industry is characterized into three major categories: synthetic fibers (polypropylene, indigo, acrylic, acetate, spandex, nylon, and polyester), protein fibers (silk, cashmere, mohair, angora, and wool), and cellulose fibers (lyocell, hemp, ramine, linen, rayon, and cotton) [21].

Textile wastewater is generated from the different processes of the textile industry based on raw materials. Various categories of wastewater are generated in sub-processes of the textile industry based on the factors pH, COD, BOD, heavy metals, and dyes that cause health issues in humans and animals [22]. The workers in textile factories are also reported with respiratory problems because of the contamination in drinking water [23]. An important chemical used in the textile industry is a dye associated with health risks to animals, plants, and humans [24].

2. Textile Manufacturing Processes

There are two textile manufacturing processes based on their products: dry fabrics and wet fabrics. In the dry manufacturing processes, the waste is majorly solids, and the liquid is dried through evaporation. In contrast, a considerable quantity of water is used at different stages in the wet processes. This review considers the textile industry's wet processes that generate numerous effluent-containing hazardous chemicals. The wet process of manufacturing fabrics consists of several stages that make the process complex, water and chemical-intensive. The seven stages are explained below that are the part of each textile manufacturing process (Fig. 2).

The first step of textile manufacturing is sizing, an important step that gives a protective coating to the yarn to avoid the breakage during the upcoming steps. The manufactured or synthetic material (wool, cotton, jute, silk, and polyester) is processed by adding polycyclic acids, poly acetate, polyvinyl alcohol (PVA), carboxymethyl cellulose (CMC), ammonia, waxes, and starch to give high potency to fibers [25-27]. The second step of textile manufacturing is desizing, which removes the sizing chemicals from the fiber by using auxiliary chemicals and enzymes to increase the fiber's absorbency. Mineral acids and bacterial enzymes have more application in desizing steps than traditional methods.

Scouring is a process of removing impurities from the fiber. This process involves washing impurities, such as non-cellulosic materials, surfactants, oils, waxes, and fats, by using alkali agents like soap or detergent, sodium hydroxide, ethers, and glycerol [25]. Bleaching is a process of whitening the fiber by removing natural coloring material. Various oxidizing agents are used in bleaching cellulosic fibers such as sodium chlorite, hydrogen peroxide, sodium hypochlorite, peracetic acid.

Mercerizing is an important step in textile manufacturing where hot and cold caustic soda increases fiber properties such as affinity, lustre, and strength. This process is carried out after the bleaching process, which is vital for shining the and increasing the absorbance of fibers for dyes. This process is used majorly for cotton fabrics with 18 to 24% concentrated NaOH [28]. The process treats the fibers by immersing the fiber in caustic soda with a short residence time that is approximately not more significant than four minutes [29]. The fiber is then washed with acid or water to neutralize the effect of caustic soda. The fiber is then elongated or comes under tension to eliminate the effect of shrinking due to the impregnation of the fiber with NaOH.

Dyeing is a major process of coloring the fiber with dyes in the textile industry, where different auxiliary chemicals are used to increase the attachment of fibers with dye molecules. This vital pro-

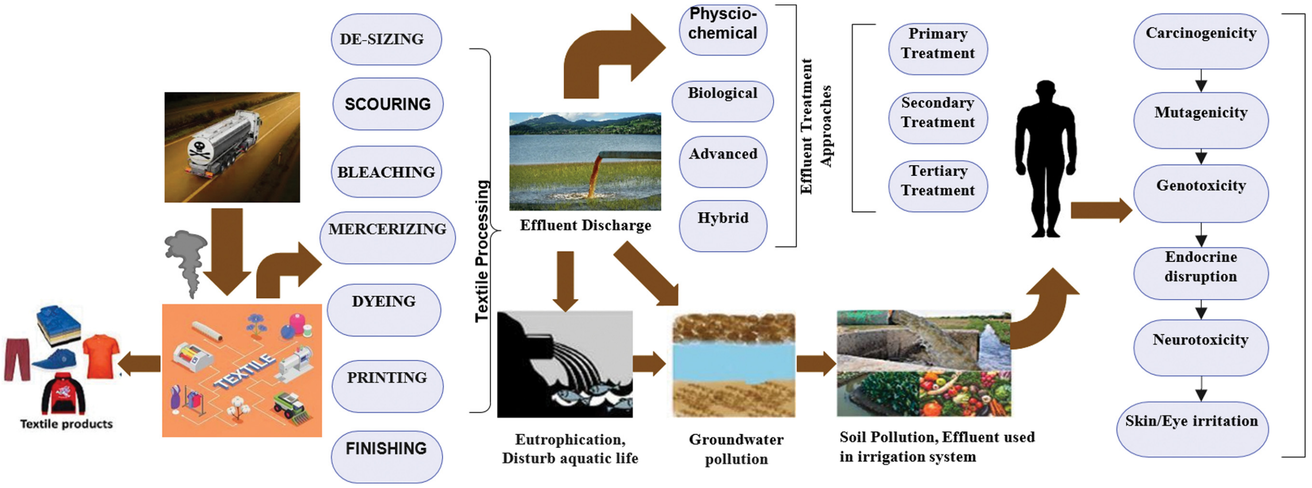


Fig. 2. Processing in the textile industry, various treatment approaches, and toxicity of textile wastewater.

Table 1. Water consumption in different stages of textile manufacturing [34]

Water usage for different fiber materials (mL/kg)	Processes in the textile industry							
	Sizing	Desizing	Scouring	Washing	Bleaching	Mercerizing	Dyeing	Finishing
Polyester			25,000-42,000				17,000-34,000	8,000-12,000
Acrylic			50,000-67,000				17,000-34,000	40,000-56,000
Nylon			50,000-67,000				17,000-340,000	32,000-48,000
Acetate			25,000-84,000		33,000-50,000			
Rayon			17,000-34,000				17,000-34,000	4,000-12,000
Wool			46,000-100,000	334,000-835,000	3,000-22,000		16,000-22,000	
Cotton	500-8,200	2,500-21,000	20,000-45,000		2,500-25,000	17,000-32,000	10,000-300,000	8,000-16,000

cess is to add colors to fiber using dyes such as metal complex dyes, direct dye, basic dye, sulfur dye, reactive acid dye, vat dye, azoic dye, and different pigments [30]. The printing stage extensively uses urea, formaldehyde, solvents, metals, dyes, and phthalates. Finishing is the final step of textile product manufacturing to maintain, protect and improve the quality and properties of the fiber. This stage includes maintenance and protection of inorganic, synthetic, or biocides in nature to maintain and improve the properties such as protection from UV damage and microbial activities, flame retardance, waterproofing, softening, and stain proofing.

3. Water Consumption in Manufacturing Process

Textile processing operations are the water-intensive processes listed in Table 1. Most fiber preparation processes use aqueous systems (water bath), including mercerizing, bleaching, scouring, desizing, dyeing and finishing. Wastewater is generated from all these processing steps, containing hazardous matter and the finishing, printing, dyeing, and pre-treatment are the potential pollution generating steps in the textile industry.

The desizing step in textile processing is the most polluted, adding weaving and sizing chemicals into the wastewater [31]. The scouring step is water intensive in wet textile processing, where waxes, oil, and dirt are removed from the fibers and washed into a wastewater stream. These two steps are collectively responsible for the 50% BOD in textile industry wastewater [32]. There are different factors on which water consumption is dependent in the textile industry. These factors are operation type (continuous, semi-continuous, batch), age and equipment used for processing, fiber to be processed, and mill size. Overall, 90-95% of the water used in textile processes ends up as effluent, and the losses are due to drying and dyeing, hot bath evaporation and steam production [33]. A large quantity of water is used in manufacturing cotton products. At the same time, silk, wool, and synthetic fibers require less water per product than cotton fiber. Table 1 summarizes the water consumption in different processing steps and fiber material used for textile products. There is more water consumption in the scouring and finishing process; wool and felted fabrics consume more in their processes than others. Different machinery used in the textile industry has different water requirements per product. Winch machines have higher water consumption per product that have liquor ration per product from 15 : 1 to 40 : 1. The other dyeing machinery uses different amounts of water per product listed in Table 2.

Table 2. Liquor ratio per product of different dyeing machines [34]

Liquor ration per product of different dyeing machines	
Dyeing machine	Liquor to product ratio
Skein	17 : 1
Stock	12 : 1
Beck	17 : 1
Package	10 : 1
Beam	10 : 1
Jig	5 : 1
Jet	7 : 1-15 : 1
Winch	15 : 1-40 : 1
Continuous	1 : 1

IMPLICATIONS AND IMPACTS OF TEXTILE WASTEWATER

1. Health Hazard of Discharged Chemicals

The textile industry uses a variety of hazardous chemicals in multiple processing steps. The textile industry involves complicated processes that produce different products using raw materials containing variously non-degradable and toxic organic and synthetic chemicals. These harmful chemicals alter the fabric's quality, which causes toxic wastewater after adding it. These auxiliary and complex structure chemicals make the wastewater effluent highly alkaline, increase biological oxygen demand (BOD), chemical oxygen demand (COD), pH, total suspended solids (TSS), and total dissolved solids (TDS) [35]. It is very hard to remove structures containing chromophoric group, dyes, highly soluble organic compounds present in the textile effluent from conventional wastewater treatment processes [19] that cause various health and environmental issues (Fig.2). It is important to discuss the impacts of untreated or poorly treated textile wastewater on environment, human health and aquatic life.

1-1. Impact on Aquatic Life

Aquatic life is at risk due to the toxicity received by the textile effluent that is continuously contaminating the water body such as rivers, oceans, ponds and lakes. Textile wastewater generation is increasing with the increasing demand for cotton. The increasing pollution caused by textile effluents in abiotic environments seriously impacts the biotic environment such as flora and fauna disruption and degradation of the water body and alteration of chemical and physical properties in soil are significantly caused by the dyes [13]. Dyes are the primary concern for aquatic life because they restrict sunlight reflection and absorption due to their high photostability and thermal characteristics. A decrease in light penetration disturb the aquatic biota's biological cycles and induces oxygen depletion due to a reduction in photosynthetic activity. The photosynthesis process of aquatic plants such as algae and aquatic life ecological development is seriously affected by the large qualities of textile dyes due to the hindrance of sunlight reflection and absorption that also limits the re-oxygenation of water. Different dyes have different effects on living things, such as congo red (CR), and reactive orange (RO) dyes are regularly used in the textile industry and hinder bacterial and algal growth [36,37]. Crystal violet (CV) dye used in the textile industry is known for its carcinogenic effects, promoting tumor growth and clastogenic nature in fishes [38]. There are toxic metals present in textile wastewater, such as Ni, Cd, Pb, Zn, Cu, Sb and Cr, which have the ability to affect the different growth parameters such as growth, seedling, germination and reduction in microbial diversity/activity [39,40]. The colored allergens are the cause of prevention of re-oxygenation and consumption of dissolved oxygen and cause eutrophication in receiving streams through biological and chemical assimilations that affect the growth of algae and other plants underwater.

Physio-chemical analysis studies of textile dyes on marine and aquatic life reveal the ecosystem disturbance, observed in underdeveloped countries where textile industries are not treating their effluents up to the standards. The physico-chemical analysis of Indian rivers, Kshipra in Ujjain city, India, by Ahmed et al. [24] shows the abnormal variation caused by textile wastewater in total solids (1,475.6 mg/L to 13,499.2 mg/L), chlorides (549.9 mg/L to 669.9 mg/L), chemical oxygen demand (310 mg/L to 345 mg/L), pH (8.6 to 9.0), and dissolved oxygen (0 to 2 mg/L). The abnormality in river water has health risks to humans as well as the aquatic life of the region. Another study analyzed the abnormal physio-chemical parameters in wastewater in ten textile industries in Pakistan [41]. They reported undesirable alterations in the quality of textile wastewater discharge. They analyzed parameters such as heavy metals (Cd, Cr, Cu, Fe, Ni, Mn and Zn), total suspended solids, chemical oxygen demand, biochemical oxygen demand, electrical conductivity, pH, total dissolved solids, and temperature.

1-2. Impact on Humans

Untreated textile wastewater severely affects human health when it goes into the water. Dyes are a serious threat to human health because they are hard to degrade from wastewater. Azo dyes have aromatic amine (1,4-diamine benzene) that induces vertigo, hypertension, gastritis, vomiting, severe tubular necrosis, rhabdomyolysis, lifelong blindness, exophthalmosis, lacrimation, chemosis, contact dermatitis, and skin irritation. The ingestion of such dyes also causes respiratory distress along with oedema of the larynx, tongue, pharynx, throat, and face [42]. Humans exposed to water stimulated with aromatic amines have the risk of altering the liver enzymes metabolism. The irrigation of crops as a result of polluted water, in the absence of freshwater, impacts human health and is reported with the symptoms of grey hair, knee pain, and teeth plaque [36]. Microtoxicity and genotoxicity are accelerated by sequestering metal ions in the textile wastewater that flow into the domestic water streams.

The carcinogenic nature of the dyes causes cerebral abnormalities, intestinal cancer, irritation to the upper respiratory tract, mucous membrane, skin such as dermatitis eyes and other respiratory diseases [43]. The reactive nature of reactive dyes with polyamide, woollen, and cellulose is also prominent in living organisms, severely impacting the health of living organisms and humans. Protein groups containing -SH and -NH2 can make covalent bonds with reactive dyes, which is a severe problem for the health of living organisms [44]. The different components and breakdown products of Azo dyes cause disturbance of blood formation and haemoglobin adducts

Table 3. Chemical composition of textile industry, toxicity, and applications [20]

Chemicals	Toxicity	Applications
Silver and nano silver compounds	Affect lung epithelial cells, neuronal cells, lungs, ecotoxicity and bacterial resistance.	These compounds are used as antibacterial and antimicrobial agents.
Tributylphosphate (TBP) and other Organophosphorus compounds	Responsible for bladder cancer in rats, irritate mucous membranes, skin, nose and eye.	Applications in heavy textiles for manufacturing rotproof, waterproof and flame-retardant material.
Dioxins	Responsible for altering metabolism, growth factor signalling and immunologic response. It can cause abnormalities in nails, skin, and teeth. The other health issues are reduced thyroid and testosterone hormones, endometriosis, porphyria, early menopause, cardiovascular dizease, diabetes, and liver and lung cancer.	Applications in heavy-duty fiber manufacturing as a fungicide (preservative).
Brominated Flame Retardants (hexabromobiphenyls, hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs), and polybrominated Biphenyls (PBPs)	These chemicals are carcinogens and Persistent organic pollutants; as per United Nations Environment Programme (UNEP), these are responsible for endocrine disruption, thyroid effects, and neurodevelopmental toxicity.	These chemicals are used to prevent burning and less-flammable material.

Table 3. Continued

Chemicals	Toxicity	Applications
Pentachlorophenol (PCP) and other Chlorophenols	These chemicals are carcinogenic and affect dermatitis, eyes, liver, blood, kidney, nervous system, cardiovascular, and immune systems.	Their applications are to prepare dyestuffs used as preservative agents in cotton bleaching and the sea transit of textile fibers.
Short-chain chlorinated paraffin (SCCP)	It is POP under Stockholm Convention, and Group 2B is a carcinogen under IARC. It causes cancer, is an endocrine disruptor, an aquatic toxicant, bio-accumulative in nature, and affects the thyroid gland, liver and kidney (Wang, Gao and Jiang, 2017).	It is a potent wetting agent in the printing process for pigment preparation.
Volatile organic compounds (1,1,1- trichloroethane, dichloromethane, methyl ethyl ketone, xylene, methyl isobutyl ketone, and toluene)	Exposure to these compounds causes off-gassing, liver and kidney damage, numb fingers, staggering, slurred speech, tremors, drowsiness, headaches, nausea, dizziness, depression and skin/eye irritation in humans.	In textile drying and printing for the preparation of the solvent-based ink.
Formaldehyde	This chemical is carcinogenic to humans, as per US Environmental Protection Agency (EPA), National Cancer Institute (NCI) and IARC, and causes respiratory problems, dermatitis, allergies irritate mucous membranes and skin.	Its application is in the finishing process for making crease-resistant cloths, water-resistant, and softer, preventing shrinking.
Perfluorooctane sulphonate (PFOS)	This chemical is also carcinogenic and causes an increase in cholesterol levels, changes thyroid hormone levels, causes attention deficit hyperactivity disorder and affects the liver, sperm quality, fertility, reproductive system, endocrine system, immune system, and reduced birth weight.	This chemical's application is to make textiles stain- and waterproof material.
Organotin compounds (TPhT: triphenyltin, TBT: tributyltin, and DBT: dibutyltin)	These compounds are responsible for breathing problems, muscular weakness, mucous membrane and eye irritation, and severe skin, affecting reproductive and immune systems.	These compounds are in the microbial breakdown of sweat to reduce body odor, and these are used in heavy-duty textiles as biocide.
Azo dyes (Reactive, remazol, orange, nitro, and methyl dyes)	These dyes are aquatic toxicant, genotoxic, mutagenic, and carcinogenic, and cause variable immunoglobulin levels, respiratory diseases, asthma and allergic dermatoses.	Azo dyes are used in the dyeing process for synthetic fibers, wool, silk, viscose, and cotton.
Heavy metals (Cr: chromium, Ni: nickel, As arsenic, Hg: mercury, Pb: lead, Cd: cadmium, and Sb: antimony)	These metals are mutagenic, carcinogenic, and genotoxic and affect the liver, kidney, blood cells, DNA and reproductive system.	These have applications in dyeing units in textiles for coloring and pigment preparations.
Phthalates (butyl benzyl phthalate (BBP) and diisononyl phthalate (DINP))	These chemicals are carcinogenic, that is, aquatic toxicants and endocrine disrupters. These have responsibility for impairing fertility and affecting the reproductive system.	These are applied to soften the cloths by coating and are extensively used in dyeing and printing operations.
Hexachlorobenzene (HCB)	This chemical is carcinogenic and affects endocrine disruption, the central nervous system, the thyroid, and the liver.	Its application is in azo pigments preparation and dye stuffing and is also used as a dyeing carrier.
Nonylphenols (NPs), nonylphenol ethoxylates (NPEs), and Alkylphenols	These highly toxic chemicals are the major causes of children's neuro-developmental delays, abnormal growth patterns, breast cancer, and endocrine disruption of animals, humans and aquatic life.	These chemicals are applied to stabilize or protect polymers and are used as dye-dispersing agents, emulsifiers, laundry detergents, and scouring agents.
Carbon disulphide (CS2)	This chemical is responsible for kidney diseases, chronic skin conditions, leukaemia, congenital disabilities, reproductive toxicity, sexual and gastrointestinal disorders, and psychiatric and neurological symptoms that CS2 also causes.	Viscose rayon fiber manufacturing is an application of CS2.
Trichloroethane (TCE) (Chlorinated solvents)	It is an ozone-depleting chemical that affects the kidney, liver, and central nervous system.	Its application is to remove impurities from fibers in scouring operations.

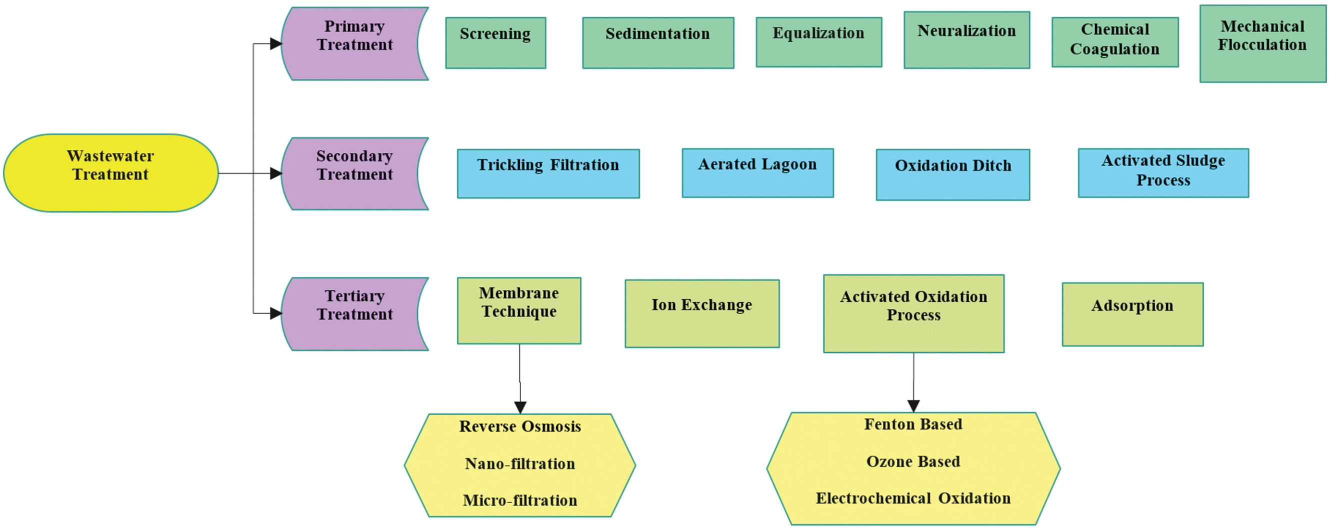


Fig. 3. Categories of wastewater treatment.

formation with the adsorption through lungs, skin, and gastrointestinal tract [45]. The electron-donating substituent ortho increases the carcinogenic nature and para position, and several azo dyes have the potential to the genesis of malignant tumors that damage the DNA. The other chemicals and compounds causing health problems are listed in Table 3.

2. Wastewater Treatment Options

Extensive research conducted on textile wastewater treatment processes includes various operations and their potential combinations to remove pollutants. The wastewater treatment processes are essential to remove the toxic and hazardous chemicals from the wastewater entering the water body. Physical, chemical, and biological treatments are the textile wastewater treatment options. These processes and technologies protect the environment from hazardous chemicals and have capability to recover the chemicals and water effectively for the purpose of reusing it. The wastewater treatments are classified into primary, secondary and tertiary wastewater treatment processes illustrated in Fig. 3.

The textile industry needs high quality, consistent water supply to manufacture textile products in different operations, and wastewater treatment discharge should meet the regulations and standards. Companies must develop and explore conventional and advanced processes and technologies to fulfil wastewater discharge standards and regulations and remain competitive. Thus, this review highlights the nature of the wastewater generated in textile industries and classifies the processes and technologies of their treatment. This review also explores the hybrid technologies that are more effective than the conventional methods to treat the textile wastewater.

TREATMENT OF TEXTILE WASTEWATER

1. Recovery Processes

Total quality management is essential to recover and reuse wastewater from the textile industry. It requires stepwise assessment and life cycle analysis of parameters of textile wastewater, including technologies to be used, identification of wastewater streams to be recovered, pollution profiles, and manufacturing process. It also evaluates the treated water quality by emphasizing the technological implications of complying with the effluent limitations and appropriate treatment [6]. The textile industry is the most polluting industry on the earth with the greatest water and chemical consumption activities. Colorants are extensively used in the dyeing textile industry that contaminate water with a 50-1,000 ppm concentration in wastewater [46]. It is essential to recover and remove the colorants and other chemicals from wastewater for the reuse or disposal purposes. Different technologies and processes are developed to recover the water and expensive chemicals and dyes. Integrating advanced technology of low-cost absorbents is significant in this area of study [47]. The water recovery processes are electrochemical processes with distillation, ultrafiltration, microfiltration, and reverse osmosis, which enable the profitable and economic recovery of valuable products and chemicals. These processes are economically not optimized for the recycling and recovering the water and other textile chemicals that need attention of the researchers.

Nanotechnology also contributes to research and development in recovering water and auxiliary chemicals from the textile wastewater. This technology includes nano-sorbent and carbon-based composites, nanosorbents including nanoclays, regenerable nanosorbent polymers and iron and carbon compounds, which are also effective in reducing the pollutants from wastewater [14]. Carbon nanotube technology can also remove antibiotics, dyes, and heavy metals from textile wastewater [48]. The other technologies are membranes that can remove germs, dyes, and oils depending on the molecule size and pore size by a simple process of differential pressure. Another advanced technology of nanoparticles combined with photocatalysts can remove antibiotics, germs, dyes, and organic compounds by the process of degradation [49]. The characteristics of these technologies are as follows: photocatalysts and membranes are highly efficient and easily applied; nanoclays, carbon nanotubes, and metal oxides are low-cost technologies [50], but these need commercial implications.

The textile industry is highly chemical- and water-intensive that requires latest and effective treatment technologies for the water and chemical recovery and their reuse. Different textile wastewater treatment methods are reported in the literature as physical, biological, advanced, and combining different treatment methods (hybrid).

2. Wastewater Treatment Methods

2-1. Biological Treatment

Various chemical and physical methods are present that cannot completely degrade the organic matter of textile wastewater. Extensive research is present on the capability of algae, fungi, and bacteria to remove the chemicals from textile wastewater; specifically, biological treatment methods play a significant role in decolorizing azo dyes [51]. Bacterial strains to decolorize the dyes were initiated by anaerobic and aerobic degradation, followed by cleavage of azo bonds and reduction through azoreductase-catalyzed anaerobic treatment. Organisms' active consortia are effective for degrading pollutants from wastewater rather than single-star species [52]. These species are ineffective due to their acclimatization in the native population, limiting their wastewater treatment capability.

Biological wastewater treatments are inexpensive, eco-friendly, green and can potentially remove the pollutants from industrial wastewater through mineralization and degradation due to their versatility and genetic diversity [20,53]. There are different methods for treating textile wastewater; the potential methods are aerobic and anaerobic or facultatively anaerobic, which are divided due to the oxygen requirement to treat the wastewater with different enzymatic or microorganisms machinery. Biological wastewater treatment methods are effective for removing or degrading dyes in the textile industry. The microorganisms used from different studies for wastewater treatment are reported in Table 4. These organisms use biosorption processes and metabolic pathways to mineralize, detoxify, degrade, and decolorize the wastewater pollutants. These methods also effectively treat turbidity, TOC, TSS, COD, BOD,

Table 4. The microorganisms used from different studies for the wastewater treatment

Textile wastewater/ Dyes	Microbial agents	Mechanism	Optimized conditions	Treatment efficiency	References
Viscose fiber Wastewater	Bacterial consortium (Pseudomonas sp., Paracoccus tibetensis, Bacillus subtilis, and Bacillus licheniformis)	Degradation	14d, shaking, 180 rpm, and 30 °C	87	[55]
Direct Blue 2B	Bacterial consortium (Bacilli, Betaproteobacteria, and Gammaproteobacteria)	Detoxification and Decolorization	48 h, static, 38.70 °C, pH 7.57, and 100 mg/L	90	[56]
Disperse Orange-3 and disperse blue-1	Anaerobic/Aerobic Algae-bacterial photobioreactor	Decolorization	8 d, 300 rpm, 38 °C, pH 7.2, 100 and 60 mg/L	99 and 96	[20]
Methyl Orange and reactive Yellow 84	Bacterial consortium (Clostridium bufermentans sp. ST12, Enterococcus sp. ST5, Oceanimonas sp. ST3, Shewanella sp. ST2)	Decolorization and Degradation	48 h, static, 35-50 °C, pH 4-8, and 100-2,000 mg/L	90	[37]
Reactive Yellow 145	Microbial and Mixed culture consortium Bacterial mixed culture (Thiosphaera sp. ATCC 35512 and Pseudomonas sp. RS1)	Decolorization and Degradation	96 h, static, 160 rpm, pH 7, and 50 mg/L	99	[57]
Reactive Red 120	Chlorella pyrenoidosa NCIM 2738	Adsorption	30 min, 25 °C, pH 3 and 50 mg/L	96	[58]
Textile effluent	Seaweed	Decolorization	300 min, 2,000 rpm, pH 5, 10 mg/L and 37 °C	84.37	[59]
Indigo dye	Phormidium autumnale	Decolorization	14 d and 25 °C	91.22	[60]
Dye effluent	Chlorella vulgaris	Biodegradation	10 d , 30 °C and pH 8	99.99	[61]
Astrazon Red	Scenedesmus oblique		48 h, 200 rpm, 25 °C, pH 6, and 200 mg/L	93.5	[62]
Remazol brilliant Blue R	Spirulina platensis	Decolorization	48 h, 30 °C, pH 6, and 100 mg/L	46.74	[63]
Methylene Blue	Microalgae and algae Scenedesmus sp.	Biosorption	120 rpm, 30 °C, 200 mg/L and pH 9	87.69	[64]
Acid red B	Pichia occidentalis G1	Degradation	16 h, 160 rpm, 30 °C, pH 5, and 50 mg/L	98	[65]

Table 4. Continued

Textile wastewater/ Dyes	Microbial agents	Mechanism	Optimized conditions	Treatment efficiency	References
Malachite Green	Pleurotus pulmonarius	Decolorization	36 h and 100 mg/L	68.6	[66]
Textile effluent	Mucor hiemalis	Detoxification	60 h, 150 rpm, 35 °C, 100 mg/L	COD (91.35) and TS (76)	[67]
Reactive Orange 16	Pichia kudriavzevii	Degradation	24 h, shaking, 120 rpm, 30 °C, pH 6 and 50 mg/L	100	[68]
Malachite Green	Pleurotus ostreatus	Decolorization	24 h, 25 °C, pH 6, and 100 mg/L	91.5	[69]
Reactive Blue 19	Trametes versiColor	Biodegradation	210 min, shaking, 120 rpm, 50 °C, pH 4 and 200 mg/L	85	[70]
Textile wastewater	Yeast culture and fungal Phomopsis sp.	Biotransformation	2.5 h, 30 °C and pH 5	99	[71]
Crystal violet	Aeromonas hydrophila	Decolorization	8 h, static, 110 rpm, 35 °C, pH 7, 50 mg/L	99	[38]
Bezema Red S2-B	Neisseria sp.	Decolorization	6 d, static, 160 rpm, 37 °C, pH 7, 100 mg/L	90	[72]
Azure B	Serratia liquefaciens	Decolorization	48 h, 120 rpm, 30 °C, pH 7.6, and 100 mg/L	90	[73]
Reactive Blue EFAF	Exiguobacterium profundumstrain	BioDecolorization	24 h, 160 rpm, pH 5-10, 50 mg/L	98	[74]
Acid Brilliant Blue GR	Halomonas sp. GT	Degradation	96 h, 30 °C, pH 7.5, 100 mg/L	100	[75]
Reactive Black 5	Bacillus sp.	Biotransformation	120 h, 25 °C, pH 9, 3.9 mg/L	97	[76]
Textile wastewater	Pseudomonas putida	Decolorization	90 h, aerobic, 80 rpm, 35 °C and pH 7	Color (87), and COD (69)	[77]
Reactive Yellow 145	Pure bacterial culture Pseudomonas aeruginosa RS1	Decolorization	24 h, static, 37 °C, pH 7, and 50 mg/L	85	[57]

and metal detoxification [54].

2-1-1. Aerobic Biological Treatment

Aerobic wastewater degradation is a naturally occurring process in the ecosystem that is driven through the microorganisms with the supply of oxygen by converting wastewater pollutants into carbon dioxide and new biomass. Different factors affect aerobic wastewater biodegradation: carbon dioxide evaluation, dissolved oxygen (DO), biological oxygen demand (BOD), and chemical oxygen demand (COD) [17]. The primary factor is assessing the biodegradability of the chemical needed to treat textile wastewater. In the textile industry, the primary pollutant is dyes and colors that have serious environmental problems and need to be treated through biological treatment [46]. The coloring components can be treated through activated sludge-based aerobic degradation followed by anaerobic treatment. During the color removal in anaerobic treatment, the aromatic amines are broken down through oxidative enzymes in aerobic microorganisms [78]. Aerobic treatment of wastewater effluent depends on the chemical structure of the degradation product and the enzymes. The discharge eluent from aerobic treatment contains toxic chemicals, such as carboxylic acids, aromatic amines, and other small organics. Aromatic amines turn into colored modules after autoxidation under aerobic conditions [78].

It is found from the literature that some facultative organisms have the ability to degrade the azo dyes biologically [79]. In Table 4, microbial agents are mentioned for their respective dye types with their mechanism, optimum condition, and efficiency. Organic carbon is needed for some strains as they cannot use dyes to grow. Under aerobic conditions, navitan fast blue SSR and textile dyes can be decolorized using pseudomonas aeruginosa in the presence of glucose [57]. Bacillus sp., halomonas sp., pseudomonas putida and other microbial agents are also effective in degrading azo dyes such as reactive black 5 [76,80], acid brilliant blue GR [75], and other wastewater components. Few bacteria in aerobic conditions grow by consuming the azo dyes and amines from reductively cleave azo bonds as carbon sources [81], but the known bacteria are in few quantities. These bacteria include pigmentiphage kullae 24 and xenophilus azovorans KF46, which can grow by consum-

Table 5. Bacterial species/strains under the anaerobic condition to remove azo dye

Name of strain	Enzyme type	% Decolorization, name of dye, and initial concentration	Conditions (time (h), temp. (°C), pH), Decolorization process	References
Staphylococcus hominis RMLRT03		94%, Acid Orange, 100 mg/l	60 h, 35 °C, 7.0, Static	[93]
Staphylococcus aureus	Azoreductase	97%, Sudan III; 76%, Orange II, 6 μg/ml	48 h, 37 °C, Degradation under static conditions	[94]
Pseudomonas sp.		83.2%, Reactive Blue 13, 200 mg/l	70 h, 35 °C, 7.0, Static	[95]
Pseudomonas sp.		83%, Reactive Black 5	24 h, 35 °C, 7.0	[96]
Pseudomonas entomophila BS1	Azoreductase	93%, Reactive Black 5	120 h, 37 °C, 5-9, Static	[97]
Pseudomonas aeruginosa	Reductive	94%, Remazol Orange, 200 mg/l	24 h, 30, 7.0, Static	[98]
Klebsiella oxytoca		96.53%, Methyl Orange, 0.3 mM	48 h, 30 °C, 7.0, Anaerobic degradation	[99]
Bacillus sp., Lysinibacillus sp.	Azoreductase	100%, Acid Yellow 36, 200 ppm	12 h, 40 °C, 7.2, degradation under static incubation	[100]
Bacillus pumilus HKG212		>95%, Remazol Navy Blue	30 h, 30 °C, 8.0, Anaerobic degradation	[101]
Bacillus cereus		97%, Reactive Red 195, 200 ppm	72 h, 37 °C, 6.0-7.5, degradation under static incubation	[102]
Acinetobacter sp. SRL8		90%, Disperse Orange SRL	30, 7.0, Microaerophilic	[103]

ing carboxy-Orange II and carboxy-Orange I, respectively [15]. Pseudomonas can decolorize reactive Red 22 sp. biologically in the presence of activated carbon [82]. At the same time, pseudomonas putida is effectively used to degrade the commercial azo dyes Orange 52, Violet 7, and Acid Yellow 17, used in the cosmetic, paper, textile, and food industries [83]. Benzidine and CI Direct Blue 38-based azo dyes in textile wastewater can be decolorized by enterococcus gallinarum [84, 85].

2-1-2. Anaerobic Biological Treatment

The anaerobic wastewater treatment process is a biological process that breaks down the effluent's contamination in the absence of oxygen through microorganisms. The azo dyes biodegradation through bacterial removal under the anaerobic treatment is a viable, non-specific, and simple process involving the breakage of azo dyes through various cytoplasmic azoreductases [86]. Colorless aromatic amines are produced under anaerobic conditions. They are impervious to anaerobic mineralization that needs to be treated in aerobic conditions because these chemicals are mutagenic to living creatures [87]. Using energy sources and complex organic carbon to carry out anaerobic wastewater treatment to remove the dyes is necessary. The structure of a dye and supplemented carbon source control the rate of dye or coloring agent removal from the wastewater [53]. Various studies present that accomplished anaerobic treatment for dye removal from textile wastewater by utilizing bacteria as microorganisms. The bacteria such as staphylococcus hominis, pseudomonas luteola, clostridium bifermentans, pseudomonas putida, and citrobacter sp. for azo dye removal under the anaerobic conditions [88]. These bacteria can remove the dye from the wastewater under aerobic conditions but are accomplished anaerobically. It is also observed that some bacteria effectively remove the azo dye under anaerobic conditions, including purple non-sulfur photosynthetic, aeromonas, proteus, micrococcus, pseudomonas, and bacillus bacteria [54]. Some bacteria also effectively decolor the azo dyes under anoxic or anaerobic conditions (Table 5).

Decolorization of dye releases aromatic amines under the anaerobic conditions by azo bond azoreductase cleavage that makes anaerobic treatment less effective and partially degrades the azo dyes. There is slow growth of methanogenic bacteria during the anaerobic conditions; as a result, this treatment method requires longer acclimatization time. However, during the anaerobic method, methane gas is generated that can be used as a renewable energy source [89]. Due to the generation of aromatic amines, the anaerobic treatment method is always carried out with aerobic treatment to meet the discharge criteria of textile wastewater by bacterial consortium. Different configurations of anaerobic reactors are developed, such as fed-batch, membrane bioreactor, fixed film, and upflow anaerobic sludge blanket (UASB), anaerobic digestion (continuously stirred tank reactors), and fluidized bed reactors for textile dyestuffs [90, 91]. Shahzad et al. [92] used an anaerobic moving bed biofilm reactor for the degradation of reactive dye present in textile wastewater that has the ability to remove COD up to 80% and color up to 70% along with the production of biogas. He also suggested AnMBBR, a cost-effective pre-treatment option for textile wastewater.

2-2. Advanced Physical Treatment Process

2-2-1. Membrane Technology

Membrane technology is an advanced technology to treat textile wastewater, and various membrane technologies are used in industries depending on reclamation and purification. Textile industries are using emerging membrane technologies, including ultrafiltration (UF), microfiltration (MF), nanofiltration (NF), and reverse osmosis (RO) in dye desalination and separation [104]. These membrane technology classes effectively remove suspended impurities, organic salts, and colors [105-107].

Reverse osmosis is a widely used membrane technology in tex-

Table 6. Membrane technologies used in textile industry for wastewater treatment

Process	Targeted pollutants	Permeability (L/ m^2 h bar)	Transmembrane pressure (TMP) (bar)	Pore size (nm)	References
Reverse osmosis	Monovalent ions	0.05-1.4	10-100		[122]
Nanofiltration	Salts (multivalent ions), dyes and lactose (sugars)	1.4-12	5-20	1-2	[123]
Ultrafiltration	Macromolecules, proteins and viruses	10-50	1-7	5-200	[124]
Microfiltration	Bacteria, suspended solids and colloids	>50	0.1-2	100-10,000	[93]
Nanofiltration or/and Ultrafiltration	Bivalent ions, and coloring compounds	7.745 for NF, and 381.7 for UF	3-13	50 for UF and approximately 2 for NF.	[125]

tile wastewater treatment processes with 94% decolorization efficiency [108], while nanofiltration is more effective than the reverse osmosis membrane technology due to the less requirement of pressure [109,110]. For example, reactive red 194, reactive yellow 145, reactive orange 16, reactive blue 15, reactive black 5, and reactive blue 2 dyes, direct, and methylene blue dyes can be removed by using polyamide, PA6DT-C, and UH004 nanofiltration membranes [105, 111-113]. Agtas et al. [114] used the UF/NF process at a pilot scale to treat real textile wastewater and came up with the results that this process can remove TOC, total hardness, Color, and COD of textile wastewater of washing baths (reactive and dispersed printing) up to 76.8%, 82%, 82.2%, and 90.1%; 76.8%, 82%, 82.2%, and 90.1% respectively. Hubadillah et al. [104] developed a bio-ceramic hollow fiber membrane based on hydroxyapatite (HAp) that effectively removes heavy metals, conductivity, turbidity, COD, and color up to 100%, 30.1%, 99.4%, 80.1%, and 99.9% respectively.

There are some advantages of using membrane technology, such as a high-quality wastewater treatment process, high purification of water/wastewater, no chemical usage, and effectiveness in removing multiple contaminants and colors [115,116]. In contrast, membrane technology is high-cost, with problems such as concentrated sludge production, high-pressure requirement, pre-treatment requirement, poor production efficiency, cleaning, scaling, clogging, and fouling [114,117]. The cost associated with using nanofiltration membrane technology to remove 76.8% of TOC, 82% of total hardness, 82.2% of color, and 90.1% of COD is approximately 90.1% of COD, including installation, operation, and membrane cost [114]. Different membrane technologies are listed in Table 6 and Table 7.

Microfiltration membrane technology is used as secondary treatment (pre-treatment) in textile wastewater treatment. A stringent treatment process allows soluble pollutants and dissolved solids to pass through its larger pore size. Hayat et al. [118] studied the combination of nanofiltration, flocculation, and coagulation to compare with microfiltration and nanofiltration. The results showed that the permeate flux of coagulation/flocculation (ca. 14 L/m^2 h) was less than the microfiltration membrane around 34 L/m^2 h. The results concluded that microfiltration gives more efficiency in removing salts, COD, and colors than coagulation/flocculation as a pre-treatment step [119,120]. Azizi et al. [121] synthesized two microfilter membranes by sintering mineral coal on a porous graphite layer with pore diameters 0.8 and 0.5 μm for real textile wastewater. The results showed a more significant permeate flux of 150 L/m^2 h, while the permeate flux value for other membranes was 4.5 L/m^2 h. The turbidity and color removal efficiency was similar for both membranes, which was 89% and 87%, respectively. The membrane of a larger diameter was able to remove 59% of the smaller diameter membranes with 48%; however, the membrane with a smaller diameter had higher salinity removal (33%) than the membrane with a larger diameter (28%).

2-2-2. Activated Carbon

Activated carbon is an adsorption technique that depends on different factors to remove heavy metals, including metal ions and adsorbent use in textile wastewater treatment. The activated carbon adsorption method can extensively remove dyes and metals in textile wastewater. The structure and characteristics of absorbents play a crucial role in removing the pollutant in textile wastewater. The removal of heavy metals is influenced by the characteristics such as size distribution, pore volume, grain size, specific surface area, and adsorption capacity [135]. Modified activated carbon is a promising technique to remove metal components from wastewater in adsorption. Moreover, adsorption capacity depends on the number of carbon atoms, the solute's affinity to the adsorbent, solute solubility in liquid, residence time or contact time [53]. The metal-contaminated wastewater is effectively treated through the activated carbon method, depending on the effect of agitation rate, adsorbent dosage, contact time, temperature, initial metal concentration and pH [136]. pH greatly influences the adsorbate's chemical speciation and adsorbent during the metal ion adsorption process in an aqueous solution [53]. The adsorption efficiency can be increased by raising the temperature during desorption [137]. The favorable temperature for adsorption is 10-45 °C, but 40 °C is the optimum temperature for adsorption [138]. Chemical solubility enhances the exothermic sorption and spontaneous reaction conditions in textile wastewater treatment systems. At different temperatures, adsorption is also taken as a physical or chemical reaction; however, maximum ions can be removed by decreasing the temperature of the exothermic desorption process [139]. According to Gupta and Gogate [140], at an elevated temperature, the cushioning effects occur, reducing the collapse intensity of cavitation and eventually decreasing the adsorption [141].

Activated carbon derived from bamboo [142], and waste tires [143] to treat textile wastewater were found effective in removing

Table 7. Various strategies, operating parameters and performances of membrane processes for treating textile wastewater

Type of wastewater	Strategy	Membrane characterization	Performance	References
Wastewater containing NaCl and Reactive Black 5	UF membrane (INSIDE CéRAM tubular)	TMP: 1-3 bar; RB conc.: 100 mg/L; NaCl conc.: 1-4 g/L	Permeate flux: ca. 220 L/m^2 h; salt rejection: ca. 40%; Dye rejection: >75%	[126]
Wastewater containing BG 4, A, BB 9, AB 1, Azure A, DB 53, AR 87	Sterlitech crossflow cell; NF	NF-270 NF membrane with an isoelectric point of 3.3	Maximum flux declines, positively charged dye molecules (51.17%), negatively charged dye molecules (48.42%). 120 L/m^2 h dye rejection and salt rejection flux that was 98% and 50%	[127]
Real textile wastewater	NF; hollow fiber configuration	Modified polysulfone fibers (trimesoyl chloride and m-phenylenediamine); Outer and inner diameter: 0.012 m and 0.0005 m	99% dye rejection for all dyes and ~3 L/m^2 h permeate flux	[128]
Wastewater containing Reactive orange 16, Reactive Black 5, RY 145, RR 15 and B 15	NF; flatsheet	Polyamide based membrane (4040-TSF-TS80-sheet)	COD (100%), all dye rejection (90%), 280.8-331.2 kL/m^2 h permeate flux	[129]
Real textile wastewater	Polyvinylidene fluoride (PVDF), hydrophobic polytetrafluoroethylene (PTFE) membrane	PVDF membrane and PTFE membrane (both have pore size 0.22 μm)	Around 96% COD and 100% color removal	[130]
Real textile wastewater	DCMD (shell side; hot feed, HF arrangement)	Nanocomposite membrane (PVDF-Cloisite 15A with 0.088 μm pore size)	90.8% COD, 93.7% TDS, 95.3% color removal and 13-22 L/m^2 h permeate flux	[131]
Wastewater containing Na_2 SO_4, RR H-E7B, Reactive Black 5, cation yellow X-2RL and RBB KN-R	UF; crossflow filtration setup	Tight UF ceramic membrane (porous Al_2O_3 with pore size of 1.16 nm, TiO_2/ZrO_2 skin layer)	98% Permeability and 43.5 L/m^2 h bar dye rejection	[80]
Wastewater containing AY 36, AR 18, CV, and MB	Direct contact membrane distillation (DCMD); flat sheet	Polytetrafluoroethylene (PTFE) membranes (0.20 μm pore size) and Hydrophobic PVDF (HVHP; 0.45μm pore sizes, and GVHP; 0.22μm)	PVDF-0.45 (100% Decolorization, and 19.53 L/m^2), PTFE (100% Decolorization and 30.33 L/m^2 h water flux)	[132]
Wastewater containing, Na_2SO_4, RB 2, CR, DR 23 and DR 80	Ultrafiltration (UF)	Tight UF membrane	With 60 g/L Na_2SO_4, all direct dyes was 98.9%, >97% dye recovery, and 98% desalination	[133]
Real textile wastewater	Hollow fiber (HF) and nanofiltration (NF) with cross and feed flow, respectively	Polyamide-imide based NF HF membrane; polyethylenimine functionalized outer surface; 31 m^2/m^3	95% removal of COD, 3,000-8,000 mg/L COD with pH: 7, T: 40 °C and ~1.5 L/m^2 h permeate flux	[119]
Real textile wastewater	NF membrane combined with cellulose nanofibers and PEI-modified mica	The membrane exhibits excellent hydrophilicity; prepared on hydrolyzed polyacrylonitrile	Low salt rejection (15.63% for Na_2SO_4, 3.42% for NaCl), excellent dye retention (98.64% for Evans Blue, 98.89% for Congo Red, and 99.66 % for Coomassie Brilliant Blue R250), and high water permeability (62.18 LMH/bar), high dye/salt separation	[134]

dyes and heavy metals. These studies also suggested that the absorption capacity of activated carbon can be enhanced by optimizing various parameters such as initial concentration of the contaminants, contact time, pH [142], temperature, and adsorbent amounts [143]. Sime et al. [144] investigated the results of dye removal from real textile wastewater by activated carbon derived from corn cobs. The experiment was performed at 90 mg/L initial dye concentration, 84 min contact time, 1.6 g/L adsorbent dose, and 6.2 pH, achieving 88% dye removal. Igwegbe et al. [145] used response surface methodology (RSM) to optimize the adsorption of pollutants from textile wastewater using activated carbon. They found that the maximum adsorption of pollutants, including color, TOC, and COD, was achieved at an adsorbent dose of 1.6 g/L, a contact time of 120 minutes, and a pH of 6.7.

2-3. Advanced Chemical (Oxidation) Processes

Refractory contaminations from the textile wastewater can be removed with competitive, fast, and emerging advanced oxidation wastewater treatment processes. Advanced oxidation processes are used at the industrial level, initially used to treat drinking water in the 1980s [146,147]. Advanced oxidation processes use UV light as high energy radiation, ZnS, GaP, TiO_2, CdS, ZnO, and Fe_2O_3 as a catalyst, as well as H_2O_2 and O_3 as oxidizing agents [18,148-150].

Sulfate radicals (SO_4^-) and hydroxyl ($OH^{\bullet}$) act as mediators in radical addition reactions, hydrogen abstraction, and electron transfer reactions produced during the AOPs. Thus, refractory compounds are effectively treated by AOPs by transforming them into the water and carbon dioxide [147,151]. Various advanced oxidation processes are currently developed, including electro-oxidation, electro-coagulation, sono-catalytic, photocatalytic, photo-Fenton, and ozonation processes to mineralize and degrade the heavy metals, dissolved solids and persistent dyes present in the textile wastewater. These emerging textile wastewater processes have disadvantages, such as generating enormous amounts of sludge for secondary treatment, needing high electrical energy, using complicated procedures, high chemical demanding, and being costly to install [18].

2-3-1. Electrochemical Oxidation

Non-degradable and toxic components of textile wastewater can be removed alternately from the electrochemical oxidation. ($OH^{\bullet}$) is a highly reactive species produced during the treatment process to mineralize and decolorize the toxic metals, dissolved solids and different coloring substances (see Scheme 1) [152,153]. Direct and indirect ways of anodic oxidation are applied to reduce TDS, BOD, COD, coloring agents and other toxic chemicals from the textile wastewater [18,109]. For example, the anodic oxidation process achieves 100% COD removal from textile wastewater [154]. Electrochemical oxidation of wastewater treatment uses different types of anode such as SnO_2, Ti/RuO_2, PbO_2, and graphite, while the BDD, Ti/PBO_2, Ti/SnO_2, and Ti/IrO_2 as electrodes [155,156]. These electrodes potentially oxidize textile wastewater's pollutants over 1.9 V [156]. BDD have characteristics to mineralize and effectively remove pollutants in textile wastewater; these characteristics involve less adsorption capacity with the inactive surface, high potential O_2 overvoltage (2.7 V), and high stability [157]. However, the cost associated with BDD is high, while the other electrodes are inefficient in low oxygen over potential [156]. Ti/RuO_2 is effective in degrading and decolorizing the dyestuffs and can reduce the textile-suspended inorganic and organic pollutants. Ti/RuO_2 has high mechanical and chemical strength with high stability, produces strong oxidants (CIO-, Cl_2, and HOCl), and high oxygen over potential [18,156,158]. The disadvantages of electrochemical oxidation processes are steam stripping, toxic metabolite generation, and high operation cost. The advantages are that they cannot require additional chemical requirements, are effective in removing toxic and persistent pollutants and have high efficiency of decolorization [5,159]. Additionally, this oxidation process has the ability to remove 69% TOC, 85% COD, and 100% coloring agents within 30 minutes and 4.8 USD/m^3 operating cost [158].

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

$$Cl_2 + H_2 O \rightarrow H+ + Cl^- + HOCl$$

$$HOCl \longleftrightarrow H^+ + OCl^-$$

$$MO_x + H_2 O \rightarrow MO_x (\bullet OH) + H^+ + e^-$$

$$MO_x (\bullet OH) \rightarrow MO_x^{+1} + H^+ + e^-$$

$$MO_x (\bullet OH) \rightarrow MO_x + \tfrac{1}{2} O_2 + H^+ + e^-$$

$$MO_x^{+1} \rightarrow MO_x + \tfrac{1}{2} O_2$$

$$MO_x (\bullet OH) + Cl^- \rightarrow MO_x (\bullet OCl) + H^+ + 2\, e^-$$

$$MO_x (\bullet OCl) + Cl^- \rightarrow MO_x^{+1} + Cl_2 + e^-$$

$$MO_x (\bullet OCl) + Cl^- \rightarrow MO_x + \tfrac{1}{2} O_2 + \tfrac{1}{2} Cl_2 + e^-$$

$$\tfrac{1}{2} R + MO_x (\bullet OH) \rightarrow \tfrac{1}{2} ROO + H^+ + e^- + MO_x$$

$$R + MOx^{+1} \rightarrow RO + MO_x$$

$$Dye + OCl^- \rightarrow CO_2 + H_2 O + Cl^- + P$$

Scheme 1. Reaction scheme of electrochemical oxidation [164].

Chen et al. [160] demonstrated a 95% removal efficiency of amaranth dye using an electrochemical oxidation process with a TiO_2-NTs/SnO_2-Sb electrode. Meanwhile, Xu et al. [161] investigated the effect of power reduction on the degradation of Rhodamine B dye. They found that the electrode remained stable while achieving high dye removal efficiency during the electrochemical oxidation. Dučić et al. [162] developed low-cost graphene-based composite electrodes for phenolic dyes, achieving an 85-95% removal efficiency in electrochemical advanced oxidation processes. Lastly, Paquini et al. [163] highlighted the advantages of using electrochemical advanced oxidation processes over conventional methods for removing azo dyes from water. The different electrochemical processes are listed in Table 8 with their coloring removal efficiencies.

2-3-2. Electro-coagulation Treatment

Electro-coagulation is a highly efficient process, broadly used to

Table 8. Different electrochemical process for color removal from textile wastewater

Electrochemical process	Dye type	Experimental conditions	Decolorization efficiency	Reference
Ozonation	Acid Red 73 (AR73)	pH=3, time=4 min, O_3/RSR-BCR, AR73=500 mg/L, Ozone dose=50 mg/L	97%	[190]
Ozonation	MO	pH=9.25, T=25 °C, time=6 min, Ni-LDH=1 g/L, MO=500 mg/L, Ozone dose=109 mg/h	100%	[191]
Ozonation	Reactive Orange 4 (RO4)	pH=9, T=20 °C, RO4=100 mg/L, Cu/SBA-15=2 g/L, time=21 min, Ozone dose=5 mg/L	100%	[192]
Photocatalytic (visible-light)	MB	time=100 min, g-C_3N_4-ZnO/Cu_2O=0.05 g, MB=30 mg/L, 500 W Xenon lamp, pH=7	91.4%	[193]
Photocatalytic (UV irradiation)	MO	time=60 min, Ag/TiO_2/biochar=0.01 g, 500 W mercury lamp, MO=20 mg/L	97.4%	[194]
Photocatalytic (UV irradiation)	MB	time=180 min, PVDF-ZnS=0.5 g, 4 W UV lamp, MB=10 mg/L, pH=6, T=25 °C	95%	[195]
Photoelectro-Fenton (solar light)	Acid Red 1 (AR1)	time=120 min, Fe^{2+}=0.4 mM, Na_2SO_4=25 mM, $\mathrm{Ti}\vert\mathrm{Ir}$-Sn-Sb oxide plate electrode, AR1=98.3 mg/L, pH=3, I=15 mA/cm^2	100%	[196]
Photoelectro-Fenton (solar light)	Acid Blue 29 (AB29)	time=100 min, Fe^{2+}=0.5 mM, Na_2SO_4=50 mM, Ti/$Ru_0 \cdot 3Ti_0 \cdot 7O_2$ electrode, AB29=233.5 mg/L, pH=3, I=50 mA/cm^2	99%	[197]
Photoelectro-Fenton (UV lamp)	RB5	time=240 min, Fe^{2+}=0.5 mM, K_2SO_4=0.1 M, MnO_2 nanoflowers gas diffusion electrode, RB5=158 mg/L, H_2O_2=11.5 mM, pH=3, E=−1.1 V *vs* Ag/AgCl	93%	[198]
Electro-Fenton	TZ	time=40 min, Na_2SO_4=50 mM, $CoFe_2O_4$/carbon felt electrode, TZ=50 mg/L, pH=3, I=8.33 mA/cm^2	97%	[199]
Electro-Fenton	Reactive Red 195 (RR195)	time=60 min, superficial oxygen velocity=0.012 cm/s, fixed bed graphite electrode, RR195=50 mg/L, pH=3, I=5 mA/cm^2	100%	[200]
Electro-Fenton	Acid Blue 25 (AB25)	time=90 min, Fe-ZSM-5=100 mg/L, AB25=200 mg/L, pH=3, I=500 mA	90%	[201]
Photo-Fenton (solar light)	Reactive Black 5 (RB5)	time=120 min, Ti/Fe_2O_3=0.4 g/L, RB5=10 mg/L, pH=2.5, H_2O_2=12 mM	100%	[202]
Photo-Fenton (LED lamp)	RB	time=50 min, NiCu@MWCNT=0.2 g/L, RB=0.04 mM, pH=3, Fe^{2+}=0.01 mM, H_2O_2=0.12 mM	98%	[203]
Photo-Fenton (visible light)	CR	time=180 min, $ZnFe_2O_4$-Cr/Mn=0.8 g/L, CR=20 mg/L, pH=6, H_2O_2=0.1 M	94.6%	[204]
Fenton	Eriochrome Black T (EBT)	time=60 min, $NiCo_2O_4$-FePc=0.5 g/L, EBT=10 mg/L, pH=4-6.7, H_2O_2=50 mM	99%	[205]
Fenton	Reactive Orange 29 (RO29)	time=120 min, RO29=10 mg/L, pH=2, pyrite=3 g/L, H_2O_2=3 mM	94.4%	[206]

remove persistent textile wastewater. The persistent pollutants in textile wastewater can be removed through this electrochemical process, such as pharmaceuticals, pesticides, surfactants, phenols, heavy metals and dyes [5]. Electro-coagulation consists of a bipolar or monopolar power supply with an anode and a cathode [165], where hazardous pollutants, aluminum (Al) and iron (Fe), are removed from the textile wastewater through electrical energy [148, 153]. Flocculants in wastewater are removed by forming hydroxide ions at the cathode [136], and contamination neutralization is done at the sacrificial anode by generating metal ions [166]. The electrodes used for electro-coagulation are graphite, mild steel, aluminum, stainless steel, and iron as single electrodes. At the same time, different electrode combinations are also effective in mineralizing and degrading real and synthetic textile wastewater, such as Fe/Fe, Fe/Al, and AI/AI [148,167,168]. The criterion for selecting an appropriate electrode is to choose a readily available electrode, easy to handle, highly efficient, with good performance and low cost [158]. Aluminum and iron are suitable electrodes for electro-coagulation to remove the pollutants in textile wastewater. Iron is a suitable electrode in an alkaline and neutral medium, while aluminum has a broader application in an acidic medium [167]. Bener et al. [167] reused textile wastewater for agriculture irrigation by treating the wastewater through electro-coagulation. The - successfully removed the textile wastewater's 18.6% COD, 42.2% TOC, 64.7% TSS, 83.5% turbidity, and 94.9% color. The electro-coagulation process is impacted by various parameters such as distance between electrodes, electrode's connection mode, current density, pH of electrolytes, time of electrolysis, and electrode materials. The advantages of electro-coagulation are that it requires electrode materials, minimal footprint, smooth operation, short treatment time, and no chemical requirement [169]. However, it generates toxic sludge, high cathode passivation, and high operation cost. The electro-coagulation process requires 0.5 A current, 7,200 s treatment time and 1.5 $/$m^3$ operation cost to achieve 95% decolorization [167].

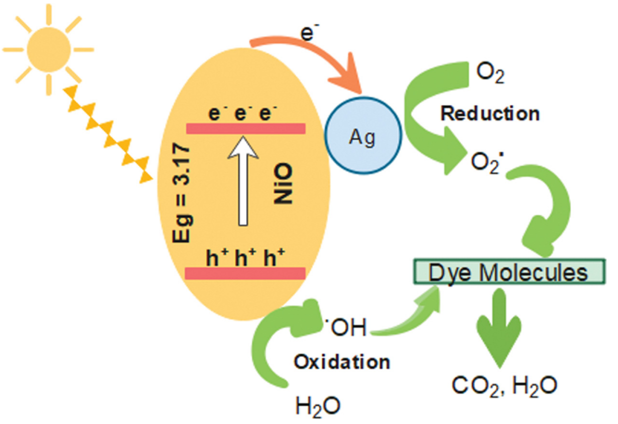
2-3-3. Sono-catalytic Process

Sonolysis is an advanced chemical oxidation method to treat textile wastewater that is not environmentally safe, has a high cost, and has poor elimination efficiency [170,171]. The sono-catalytic process is used in many textile industries to detoxify persistent compounds. The semiconductors such as $KNbO_3$, CdS/TiO_2, and CdSe are used as a catalyst in removing hazardous chemicals, dye content, suspended solids, and organic load from textile wastewater [18,155,172]. Different nanocomposite materials (TiO_2-BC, CdSe/GQDs, and Fe_3O_4-graphene/ZnO/SiO_2) are used to remove different dyes (reactive blue 69 dyes, rhodamine B, methyl orange, and methylene blue), inorganic refractory chemicals, and dissolved solids from the textile wastewater [173]. Asgari et al. [151] removed TOC, COD, and mineralized acid blue 113 from real textile wastewater through sono-photolytic-activated ZnO/persulfate. The merits of this oxidation process are that it is efficient in removing non-biodegradable or toxic compounds with short time requirements. However, it requires high dissolved oxygen and operating costs [18]. Sono-catalysis process is estimated to cost ~154.6 $/$m^3$ to decolorize the dyes up to 90% with US/UV/ZnO/PS [151].

Sheydaei and Khataee [174] treated the textile wastewater utilizing sonocatalytic decolorization by synthesizing γ-FeOOH nanoparticles that exhibited high sonocatalytic activity in removing dyes from the wastewater. Rai et al. [175] modelled artificial neural network (ANN) and response surface methodology (RSM) to find the effect of parameters of removing turbidity, COD, and colors from the textile wastewater using ultrasonic-assisted oxidation. The model successfully predicted the removal efficiencies of 79%, 66%, and 97% for turbidity, COD, and color, respectively, at the optimum conditions of ultrasonic power 420 W, processing duration 21.5 minutes, current density 15.7 mA/cm^2, and pH 7.3.

2-3-4. Photocatalytic Treatment

A photocatalytic approach to textile wastewater treatment is emerging to treat the different xenobiotic contaminates. Band gap excitation irradiates electron holes that are important for the semiconductors' photoactivation [151,157,176]. Oxidation and reduction processes occur near the photo-excited particle surface [18] shown in Scheme 2. Hydroxyl radicals are generated by reacting holes with electron donors and generating light [147]. Hydroxyl radical has the ability to mineralize organic compounds into non-toxic forms [18,177]. In photocatalytic treatment, highly reactive species (O^{-2}, $OH^{\cdot}$, O_3, and H_2O_2) are generated by using semiconductor catalysts such as ZnS, $S_2O_8^{-2}/Fe^{+2}$, α-Bi_2O_3-ZiO, TiO_2/UV, Fe_2O_3, SA/TiO_2, GaP, CuNPs, ZnO, CdS, and TiO_2 [146,155,176]. These species are highly effective in detoxifying and mineralizing organic pollutants, refectory organic and POPs for textile wastewater treatment [157,178].



Scheme 2. Schematic diagram of photocatalytic dye degradation [179].

TiO_2 is a widely used semiconductor for the treatment of textile wastewater [180]. For instance, Fazal et al. [176] treated dye-simulate wastewater to achieve 99.20% photodegradation efficiency using a biochar-TiO_2 composite. Saratale et al. [177] degraded reactive green 19 A dye in textile wastewater by using photocatalytic degradation and co-precipitation techniques to synthesize CuO/$Cu(OH)_2$ nanostructures. Photocatalytic treatment has the advantages of reducing a considerable amount of COD, high stability, removal of persistent compounds effectively, less chemicals consumption, and being short and time-consuming [181,182]. For instance, photocatalytic treatment has the ability to remove 100% coloring compounds from textile wastewater within 30 minutes. Photocatalytic treatment can remove 87% of COD by consuming fewer chemicals, such as $S_2O_8^{2-}$=4 mM, Fe^{+2}=0.2 mM, for 3 hours [183]. However, this process has problems separating the exemplary catalyst from effluent, forming by-products, fouling catalysts, restricted application related to light, and high treatment cost [18, 146].

2-3-5. Photo-Fenton Process

The photo-Fenton process (UV/Fe_2+/H_2O_2) is an emerging technology in removing pollutants and toxic compounds for industrial wastewater treatment. It can remove, degrade and decolorize the pollutants from the textile wastewater, such as metal, TDS, TOC, BOD, COD, and dyes [18]. But this advanced oxidation process has some disadvantages, such as (1) it effectively removes the pollutants in the acidic condition while the textile wastewater is alkaline [165,184]. (2) Radical generation efficiency is decreased due to the formation of ferric-organic complexes. (3) The light penetration power is decreased due to colored pollutants. In addition, (4) radical generation can also be decreased due to the inorganic ion-ferric complexes' formation due to a high load of inorganic ions (Cl^-, CO^{-3}, and SO_4^{-2}) [69,98,155]. The addition of oxalic acid can significantly minimize the drawbacks of the photo-Fenton process.

The ferrioxalate complex is responsible for the blockage of the stable complexes production between organic species and ferric ions [157]. It also increases the production of hydroxyl radicals by increasing the ferric ions regeneration and quantum yield [148, 155,178]. For example, synthetic cotton textile wastewater can be treated with PF/Ferrioxalate [157,171]. The oxalic acid addition in the photo-Fenton process with little iron precipitation can mineralize and degrade the textile wastewater.

The photo-Fenton method has advantages in that at the lower dose of ferrous sulfate, and it is more effective than the Fenton processes due to the UV radiation benefits. This method also removes persistent compounds, COD and coloring compounds [185]. The disadvantages of this method involve high operational cost, ineffective in removing copper phthalocyanine dye, and less catalytic power. The treatment depends on factors like the generated disposal of precipitate, energy consumption, and raw material used during the process. The estimated cost of the photo-Fenton process was 3.4 €/FU [18].

2-3-6. Ozonation

Ozonation is an advanced chemical process carried out chemically to degrade and mineralize textile wastewater pollutants. The persistent pollutants in textile wastewater decompose in ozonation by the non-selective and robust oxidizing agent (Ozone) [149,186]. During this advanced oxidizing process, heavy metals, dissolved solids, and persistent dyes are detoxified and decolorized rapidly by producing highly reactive species (radicals and hydroxyl) [148, 176]. Various studies have been identified on removing Pb, Cd, Cr, Sb, TS, TDS, COD, BOD, TOC, and various dyes through the ozonation process from textile wastewater [149,186,187]. Faghihinezhad et al. [188] investigated catalytic ozonation by using a novel catalyst, magnetic oxidized g-C_3N_4 modified with Al_2O_3 nanoparticles for real textile wastewater. The catalyst exhibited high efficiency in removing the organic pollutants from the textile wastewater. The separation of pollutants from textile wastewater is also facilitated by the magnetic properties of catalysts. Shokouhi et al. [189] experimented with an aqueous saline solution polluted with reactive blue 194 azo dye through ozonation supported with activated carbon as a catalyst. They found 95% dye removal efficiency at optimum conditions such as initial dye concentration, temperature=50 °C, and pH=5.

The significant merits of this process are that it does not alter the volume and can quickly remove colors from the textile wastewater. In comparison, the disadvantages include high treatment cost (~3.4 €/FU), sludge disposal problems, sensitivity to pH, short half-life (20 min), and application for gaseous state only [148,155].

COMBINED TECHNOLOGIES OF WASTEWATER TREATMENT

Various combined approaches (biological, chemical and physical) are used for better mineralization and degradation of textile wastewater treatment compared to the technologies and approaches used as single [18,207]. The textile industry discharges enormous amounts of wastewater from various coloring and hazardous compounds such as disinfectants, heavy metals, salts, surfactants, softeners, and dyes [208]. Biological processes are widely used but are time-consuming for the complete decolorization and degradation of textile wastewater [209]. So, combined or hybrid wastewater treatment processes, like biological, chemical and physical, are better in the degradation and decolorization of textile wastewater pollutants than using a single process [207,209]. For example, biological

Table 9. Combined biological, advanced oxidation and physicochemical approaches in textile wastewater treatment

Textile wastewater and dyes	Combined treatment approaches	Treatment efficiency	Optimum parameters	References
Textile wastewater	Combined anaerobic-ozonation process	Color (100%) and COD (90%)	6 min ozonation, 3 days HRT during biological treatment, textile wastewater (100-1,000) mgL^{-1}	[211]
Azo dye AR18 (AR18) and (500 mg/L)	Fenton process as post-treatment and SBR (sequencing batch reactor)	COD (97%) and Color (100%)	H_2O_2 and zero-valent iron (ZVI) with ultrasonic irradiation	[121]
Textile wastewater	Chemical+ Biological treatment	COD (87%) and Color (>92%)	100% sample with pH 3	[118]
Textile wastewater	Simultaneous chlorine photolysis treatment+ Photo-assisted electrochemical	The photo-assisted method was effective in removing 92% TOC and 86% COD as compared to the alone electrochemical method, which has efficiency (72% and 62%)	NaCl (0.3 mol/dm^3) and 1.5 A	[212]

Table 9. Continued

Textile wastewater and dyes	Combined treatment approaches	Treatment efficiency	Optimum parameters	References
Textile wastewater	Coagulation/ flocculation (CF) combined with forward osmosis (FO)	95%	NaCl 2 M and 36.0 L m^{-2} h^{-2}	[213]
Textile wastewater	Fenton or photo-Fenton (AOP) treatment+ Coagulation-flocculation (C-F) sequential	87%	H_2O_2 dose=19.6 mM (2 mL/L), 90 min, and pH=3. Fe^{+2} concentration=1 mM. $Al_2(SO_4)_3$ with pH 9.96=700 mg/L	[158]
Textile wastewater	Ultrafiltration (UF) treatment+Fenton	TOC (1.2 mg/L), COD (48 mg/L), and Color (>99%)	Fenton=vessels=9 L, 60 min, TMP=0.5-1 bar, and rpm=300 UF=membrane (FP100 and FP200), water flux=0.053 and 0.0732.	[214]
Textile wastewater reuse	Ozonation (O_3) treatment+ Electrocoagulation (EC)	95%	O3=stirred cell=1 L, Qin 40 L/h, feeding parameter=Co_3 42 mg/L, and rpm=200. EC=reactor=2 L, T=23±5 °C, voltage range=0-150 V, current density=100 mA/cm^2 and 20 mA/cm^2.	[148]
Textile wastewater	Photocatalysis+ Adsorption	99.20%	Adsorption=dye=5.0 mg/L, rpm=140, and 30 min, T=27 °C and pH=6.1. Photocatalysis=Dye=5.0 mg/L, T=60 min, T=25 °C, pH=6-7, voltage=500 W, and rpm=140.	[176]
Textile wastewater	Regenerated granular activated carbon treatment+Ozonation (O_3/rGAC)	O_3/rGAC was more effective than ozonation by 1.6-2.0 times for the removal of toxic wastewater pollutants such as recalcitrant chromophores, color, and organic load	BAC=25-100 min, aeration=3 : 1, height=55 cm and diameter=11.5 cm. Ozonation=5 min. height=50 cm, ozone dosage=18.5 mg/L. diameter=4 cm	[187]
Methylene blue	Microbial fuel cell (MFC)+Plasma oxidation (PO)	97.7%	MFC=30 min, T=450 °C, pH=7, dye=300 mg/L, and chamber long/diameter=4/3 PO=voltage 25-40, dye=300 mg/L, height= 120 and 360 mm, diameter=25 and 45 mm.	[207]
Real textile wastewater	Biological+ photocatalysis treatment	TOC (99.8%) and color (95.7%)	Photocatalysis=simulated dyes wastewater= 50 mg/L, ZnO/PPy=25 : 1. Biological=24 h, rpm=125, T=25 °C and pH=7	[146]
Real textile printing wastewater	Ultrafiltration+ nanofiltration (UF-NF) treatment	Hardness (68%), TOC (86.4%), COD (89%), and color (83.5%)	UF/NF=support layer=Al_2O_3/ Al_2O_3/ZrO_2, active layer=Al_2O_3/TiO_2, pH=0-14/0-14, pore size=0.05 μm/1 kDa, channel diameter (mm)=0.3/0.3, and channel number 19/19.	[114]
Real textile wastewater	Photocatalytic+ sonocatalytic	95% removal of organic material	Reaction time of 120 minutes, pH of 7, catalyst dosage of 0.15 g/L, Power density=200 W	[215]

process combined with advanced oxidation processes is a practical approach to treating the contamination and persistent chemical in textile wastewater [209]. During the advanced oxidation process, the pollutants are broken down into more biodegradable products by free radicals. These products then undergo a biological process using oxidoreductase enzymes that converts these products into simpler, small and less toxic metabolites [146,209]. Some disadvantages are associated with the wastewater treatment approaches that make them ineffective in the treatment processes. For instance, due to the generation of toxic products, incomplete mineralization and high cost, advanced oxidation processes are not feasible to carry out at a large scale.

The photocatalysis and biological system by Ceretta et al. [146] removed TOC by 99.8% and color by 95.5% from the real textile wastewater. The ceramic UT-NF combined system effectively removed 68% hardness, 86.4% TOC, 89% COD, and 83.5% color from the real printing wastewater [114,210]. A granular activated carbon regeneration system combined with catalytic ozonation was developed by Wang et al. [187] for textile wastewater treatment. Sun et al. [207] used a microbial fuel cell (MFC) with plasma oxidation that was effective in the mineralization and removal of 97.7% of methylene blue dye and up to 519 $\mathrm{mWm^{-2}}$ electrical energy generation. Table 9 summarizes the combined biological, advanced oxidation and physico-chemical approaches effective in treating textile wastewater.

The major pluses of these combined textile wastewater treatment approaches are that they are efficient in removing contaminates with less operational time and efficient for non-biodegradable and toxic wastewater components. Still, these approaches are costly and generate a large amount of sludge. For example, ~154.6 $\$/m^3$ cost is estimated for 90% removal of AB113 dye through the US/UV/ZnO/PS process [151].

CHALLENGES AND FUTURE PERSPECTIVE

Wastewater from the textile industry is a potential water source to reuse and can also irrigate agriculture fields. Microbial degradation is a promising method to treat textile wastewater. Still, it requires more time than other treatment techniques, whereas mixed culture can reduce the treatment time and improve pollutant removal. There are some effective methods present that can also remove the pollutants from textile wastewater, such as membrane technology, advanced oxidation processes and combined processes [9]. Membrane technology performs better when combined with electrocatalysis, electro-Fenton, and photoelectron-catalysis. But these combined technologies are emerging and need improvement in cost-effectiveness, membrane fouling and blockage, which are the significant challenges in membrane technology.

Future studies should develop bioremediation processes based on multicultural and pure cultures, which can improve the pollutants removal from textile wastewater to achieve desired wastewater characteristics by applying metabolic, proteomics and genetic engineering approaches [216]. Research should focus on membranes with anti-blockage and anti-fouling properties to resolve the limitations of membrane fouling and blockage. Studies should also evaluate the products' degradation toxicity and production of value-added products from pollutants. It is also suggested that the economic and feasibility studies of the degradation processes and methods are the potential areas of study. Overall, a scale-up of the technologies and processes is required by focusing on the sustainability of integrating the textile wastewater treatment technologies with simultaneous reuse and recovery of the valuable chemicals.

CONCLUSION

The textile industry is a major source of water and environmental pollution that has severe health effects on living organisms. The textile industry regularly discharges millions of persistent chemicals and colors worldwide. Textile wastewater contains high concentrations of xenobiotics and toxic pollutants that have a more extended stay in the environment and are damaging ecologically. Treatment of textile wastewater is challenging as no economically feasible approach is present. Although many emerging and traditional textile wastewater treatment approaches are reported, the physicochemical approach effectively removes textile wastewater colors. The disadvantage of this approach is the generation of undesired secondary pollutants and high operating costs.

Contrarily, microbial approaches are globally accepted as eco-friendly and cost-effective in removing pollutants from textile wastewater, but these have restrictions related to the long treatment time. Thus, textile wastewater treatment requires more research to effectively remove contaminants and pollutants and reduce public health and environmental impacts. Combined wastewater treatment approaches seem to remove persistent and toxic chemicals effectively. In addition, this review reports different advanced oxidation processes effective in treating persistent/xenobiotics of textile wastewater. But these approaches need to reduce the high operating cost and amount of secondary pollutants from the textile wastewater.

Membrane technology is extensively used in achieving the required quality of wastewater. Membrane bioreactors are a prominent technique used in the textile industry that is advanced to the enhanced membrane bioreactor for effective treatment with a high cost of operation. Furthermore, combined biological, chemical, and physical approaches potentially emerged in detoxification, mineralization and degradation of the various textile wastewater auxiliary chemicals and dyes.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (No.2022R1A5A1032539).

REFERENCES

1. B. R. Bruns and R. S. Meinzen-Dick, *Combining and crafting institutional tools for groundwater governance*, Intl. Food Policy Res. Inst., Washington (2023).
2. A. Boretti and L. Rosa, *NPJ Clean Water*, **2**, 15 (2019).
3. M. M. Rahman, M. A. Rahman, M. M. Haque and A. Rahman, *Sustainable water use in construction*, Tam, V. W. Y. and Le, K. N., Eds., Butterworth-Heinemann, U.K. (2019).
4. R. Chakraborty and F. Ahmad, *J. Clean. Prod.*, **340**, 130825 (2022).
5. Y. G. Park, *Environ. Eng. Res.*, **7**, 21 (2002).
6. H. U. Farouk, A. A. A. Raman and W. M. A. W. Daud, *J. Ind. Eng. Chem.*, **33**, 11 (2016).
7. C. R. Holkar, A. J. Jadhav, D. V. Pinjari, N. M. Mahamuni and A. B. Pandit, *J. Environ. Manage.*, **182**, 351 (2016).
8. L. Suhadolnik, A. Pohar, U. Novak, B. Likozar, A. Mihelič and M.

Čeh, *J. Ind. Eng. Chem.*, **72**, 178 (2019).

9. A. A. Babaei, B. Kakavandi, M. Rafiee, F. Kalantarhormizi, I. Purkaram, E. Ahmadi and S. Esmaeili, *J. Ind. Eng. Chem.*, **56**, 163 (2017).
10. Z. Wang, M. Xue, K. Huang and Z. Liu, *Adv. Treating Text. Effluent*, **5**, 91 (2011).
11. W. H. Organization, World Health Organization (2006).
12. J. H. J. Ensink, R. W. Simmons and W. v. d. Hoek, CABI Publishing, Wallingford UK (2004).
13. I. Mahboob, I. Shafiq, S. Shafique, P. Akhter, M. Munir, M. Saeed, M. S. Nazir, U. e. S. Amjad, F. Jamil, N. Ahmad, Y.-K. Park and M. Hussain, *Chemosphere*, **311**, 137180 (2023).
14. S. Sikiru, O. A. Ayodele, Y. K. Sanusi, S. Y. Adebukola, H. Soleimani, N. Yekeen and A. A. Haslija, *J. Environ. Chem. Eng.*, **10**, 108065 (2022).
15. K. Sarayu and S. Sandhya, *Appl. Biochem. Biotechnol.*, **167**, 645 (2012).
16. B. Bhaduri, A. K. Dixit and K. M. Tripathi, *New trends in emerging environmental contaminants*, P. Singh, S., Agarwal, A. K., Gupta, T. and Maliyekkal, S. M., Eds., Springer Singapore, Singapore (2022).
17. S. Mishra, V. Singh, B. Ormeci, A. Hussain, L. Cheng and K. Venkiteshwaran, *J. Environ. Manage.*, **327**, 116898 (2023).
18. K. Paździor, L. Bilińska and S. Ledakowicz, *Chem. Eng. J.*, **376**, 120597 (2019).
19. M. M. Hassan and C. M. Carr, *Chemosphere*, **209**, 201 (2018).
20. R. Kishor, D. Purchase, G. D. Saratale, R. G. Saratale, L. F. R. Ferreira, M. Bilal, R. Chandra and R. N. Bharagava, *J. Environ. Chem. Eng.*, **9**, 105012 (2021).
21. N. Athira and J. D. S, *Nat. Environ. Pollut. Technol.*, **17**, 25 (2018).
22. European Parliament (2020). Europa.eu., https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93327/the-impact-of-textile-production-and-waste-on-the-environment-infographic (Data accessed 2023).
23. M. Khan, K. Muhmood, S. Noureen, H. Z. Mahmood and R. Amir-ud-Din, *Int. J. Occup. Saf. Ergon.*, **28**, 184 (2022).
24. F. Parvin, S. Islam, S. I. Akm, Z. Urmy and S. Ahmed, *Biomed. J. Sci. Tech. Res.*, **28**, 21831 (2020).
25. P. Wang, R. Hu, X. Huang, T. Wang, S. Hu, M. Hu, H. Xu, X. Li, K. Liu and S. Wang, *Adv. Mater.*, **34**, 2110590 (2022).
26. Z. He, K. P. Tran, S. Thomassey, X. Zeng, J. Xu and C. Yi, *J. Manuf. Syst.*, **62**, 939 (2022).
27. A. S. Reddy, S. Kalla and Z. Murthy, *Environ. Eng. Res.*, **27**, 210228 (2022).
28. R. Sana, J. Mounir, K. Foued, E. O. Asma, M. Slah and D. Bernard, *J. Nat. Fibers*, **19**, 15948 (2022).
29. K. G. Pavithra and V. Jaikumar, *J. Ind. Eng. Chem.*, **75**, 1 (2019).
30. M. Rahimi, E. Salehi, M. Mandooie and N. Khalili, *J. Ind. Eng. Chem.*, **120**, 271 (2023).
31. S. Şahinkaya, *J. Ind. Eng. Chem.*, **19**, 601 (2013).
32. S. Zhang, C. Xu, R. Xie, H. Yu, M. Sun and F. Li, *Sci. Total Environ.*, **857**, 159495 (2023).
33. K. M. Shah, I. H. Billinge, X. Chen, H. Fan, Y. Huang, R. K. Winton and N. Y. Yip, *Desalination*, **538**, 115827 (2022).
34. P. S. Kumar, K. G. Pavithra and Ramalingam, *Carbonaceous composite materials*, Materials Research Foundations, Millerville (2018).
35. P. H. Nakhate, C. R. Gadipelly, N. T. Joshi and K. V. Marathe, *J. Ind. Eng. Chem.*, **69**, 77 (2019).
36. V. V. Chandanshive, N. R. Rane, A. S. Tamboli, A. R. Gholave, R. V. Khandare and S. P. Govindwar, *J. Hazard. Mater.*, **338**, 47 (2017).
37. M. Zhuang, E. Sanganyado, X. Zhang, L. Xu, J. Zhu, W. Liu and H. Song, *J. Environ. Manage.*, **261**, 110222 (2020).
38. R. N. Bharagava, S. Mani, S. I. Mulla and G. D. Saratale, *Ecotoxicol. Environ. Saf.*, **156**, 166 (2018).
39. V. Chandanshive, S. Kadam, N. Rane, B.-H. Jeon, J. Jadhav and S. Govindwar, *Chemosphere*, **252**, 126513 (2020).
40. F. Xue, B. Tang, L. Bin, J. Ye, S. Huang, F. Fu, P. Li and J. Cui, *Sci. Total Environ.*, **657**, 696 (2019).
41. S. Muhammad, M. T. Shah and S. Khan, *Food Chem. Toxicol.*, **48**, 2855 (2010).
42. S. K. Kadam, A. D. Watharkar, V. V. Chandanshive, R. V. Khandare, B.-H. Jeon, J. P. Jadhav and S. P. Govindwar, *J. Clean. Prod.*, **203**, 788 (2018).
43. A. Azanaw, B. Birlie, B. Teshome and M. Jemberie, *CSCEE*, **6**, 100230 (2022).
44. R. W. Horobin, J. C. Stockert and H. Zhang, *Color. Technol.*, **138**, 3 (2022).
45. S. Thanigaivel, A. Priya, L. Gnanasekaran, T. K. Hoang, S. Rajendran and M. Soto-Moscoso, *Sustain. Energy Technol. Assess.*, **53**, 102484 (2022).
46. M. Ikram, M. Naeem, M. Zahoor, M. M. Hanafiah, A. A. Oyekanmi, R. Ullah, D. A. A. Farraj, M. S. Elshikh, I. Zekker and N. Gulfam, *Water*, **14**, 2063 (2022).
47. S. Merouani, A. Dehane, A. Belghit, O. Hamdaoui, N. E. H. Boussalem and H. Daif, *Adv. Environ. Sci.*, **1**, 192 (2022).
48. S. S. Qureshi, V. Shah, S. Nizamuddin, N. Mubarak, R. R. Karri, M. H. Dehghani, S. Ramesh, M. Khalid and M. E. Rahman, *J. Mol. Liq.*, **356**, 119045 (2022).
49. H. R. Dihom, M. M. Al-Shaibani, R. M. S. R. Mohamed, A. A. Al-Gheethi, A. Sharma and M. H. B. Khamidun, *J. Water Process. Eng.*, **47**, 102705 (2022).
50. D. López-Rodríguez, B. Micó-Vicent, M. Bonet-Aracil, F. Cases and E. Bou-Belda, *Int. J. Mol. Sci.*, **23**, 9671 (2022).
51. R. Al-Tohamy, S. S. Ali, F. Li, K. M. Okasha, Y. A.-G. Mahmoud, T. Elsamahy, H. Jiao, Y. Fu and J. Sun, *Ecotoxicol. Environ. Saf.*, **231**, 113160 (2022).
52. D. Bharathi, J. G. T. Nandagopal, R. Ranjithkumar, P. K. Gupta and S. Djearamane, *Arch. Microbiol.*, **204**, 169 (2022).
53. Y. B. Jo, J. S. Cha, J. H. Ko, M. C. Shin, S. H. Park, J.-K. Jeon, S.-S. Kim and Y.-K. Park, *Korean J. Chem. Eng.*, **28**, 106 (2011).
54. R. Kishor, R. N. Bharagava and G. Saxena, CRC Press, 1 (2018).
55. R. Kishor, A. Raj and R. N. Bharagava, *J. Water Process. Eng.*, **47**, 102700 (2022).
56. J. Cao, E. Sanganyado, W. Liu, W. Zhang and Y. Liu, *J. Environ. Manage.*, **242**, 229 (2019).
57. N. Garg, A. Garg and S. Mukherji, *J. Environ. Manage.*, **263**, 110383 (2020).
58. S. Sinha, R. Singh, A. K. Chaurasia and S. Nigam, *J. Hazard. Mater.*, **306**, 386 (2016).
59. K. Amaraselvam, S. Sharmila and L. Jeyanthi Rebecca, *Int. J. Pharm. Technol.*, **8**, 15740 (2016).
60. P. Dellamatrice and M. Silva-Stenico, *Braz. J. Microbiol.*, **48**, 25 (2017).
61. S. Devaraja, M. Bharath, K. Deepak, B. Suganya, B. Vishal, D. Swa-

minathan and N. Meyyappan, *Adv. Biotechnol. Microbiol.*, **6**, 27 (2017).
62. S. Cengiz Sahin and S. Aksu, *Anal. Lett.*, **50**, 1812 (2017).
63. S. Afreen, F. Bano, N. Ahmad and T. Fatma, *Biocatal. Agric. Biotechnol.*, **10**, 403 (2017).
64. F. Afshariani and A. Roosta, *J. Clean. Prod.*, **225**, 133 (2019).
65. L. Song, Y. Shao, S. Ning and L. Tan, *Bioresour. Technol.*, **233**, 21 (2017).
66. V. V. Leo, A. K. Passari, I. K. Muniraj, S. Uthandi, A. Hashem, E. F. Abd_Allah, A. A. Alqarawi and B. P. Singh, *Saudi J. Biol. Sci.*, **26**, 464 (2019).
67. A. H. Molla and H. I. Khan, *Environ. Sci. Pollut. Res.*, **25**, 10820 (2018).
68. C. M. Rosu, M. Avadanei, D. Gherghel, M. Mihasan, C. Mihai, A. Trifan, A. Miron and G. Vochita, *Water, Air, & Soil Pollut.*, **229**, 1 (2018).
69. R. Zhuo, J. Zhang, H. Yu, F. Ma and X. Zhang, *Chemosphere*, **234**, 733 (2019).
70. M. Y. Dauda and E. A. Erkurt, *J. Hazard. Mater.*, **393**, 121555 (2020).
71. K. K. Navada and A. Kulal, *J. Environ. Chem. Eng.*, **8**, 103550 (2020).
72. M. E. Karim, K. Dhar and M. T. Hossain, *J. Genet. Eng. Biotechnol.*, **16**, 375 (2018).
73. I. Haq and A. Raj, *Chemosphere*, **196**, 58 (2018).
74. R. B. Bose, M. Thillaichidambaram, B. Paulraj, K. Narayanan, N. Ganesan, R. C. Muthiah and R. K. Murugesan, *Biocatal. Agric. Biotechnol.*, **16**, 98 (2018).
75. F. Tian, G. Guo, C. Zhang, F. Yang, Z. Hu, C. Liu and S.-w. Wang, *Int. J. Biol. Macromol.*, **123**, 1062 (2019).
76. W. C. Wanyonyi, J. M. Onyari, P. M. Shiundu and F. J. Mulaa, *Energy Procedia*, **157**, 815 (2019).
77. S. K. Sen, P. Patra, C. R. Das, S. Raut and S. Raut, *Water Resour. Ind.*, **21**, 100106 (2019).
78. J. M. Bidu, K. N. Njau, M. Rwiza and B. Van der Bruggen, *SAJCE*, **43**, 112 (2023).
79. S. Zafar, D. A. Bukhari and A. Rehman, *Saudi J. Biol. Sci.*, **29**, 103437 (2022).
80. X. Ma, P. Chen, M. Zhou, Z. Zhong, F. Zhang and W. Xing, *Ind. Eng. Chem. Res.*, **56**, 7070 (2017).
81. V. K. Mukkera and S. Katuri, *Innovative Trends in Hydrological and Environmental Systems: Select Proceedings of ITHES 2021*, 821 (2022).
82. A. Fareed, H. Zaffar, M. Bilal, J. Hussain, C. Jackson and T. A. Naqvi, *Plos One*, **17**, e0269559 (2022).
83. H. Zhang, K. Zhang, M. Gao, Z. An, C. Tang and X. Yan, *J. Water Process. Eng.*, **50**, 103233 (2022).
84. A. Srivastava, L. K. Dangi, S. Kumar and R. Rani, *Heliyon*, **8**, e08834 (2022).
85. A. Sen and A. Nigam, *J. Sci. Res.*, **66**, 66 (2022).
86. P. Panwar, P. Mahajan and J. Kaushal, *Biological approaches in dye-containing wastewater*, Volume 2, A. Khadir, S. S. Muthu, Eds., Springer Singapore, Singapore (2022).
87. A. K. Alsukaibi, *Processes*, **10**, 1968 (2022).
88. R. P. Singh, P. K. Singh and R. L. Singh, *Toxicol. Int.*, **21**, 160 (2017).
89. T. Xie, C. Herbert, D. Zitomer, L. Kimbell, M. Stafford and K. Venkiteshwaran, *Chem. Eng. J.*, **453**, 139788 (2023).
90. J. K. Biswas, A. Mitra, M. P. Shah and S. Rodriguez-Couto, *Development in wastewater treatment research and processes*, Shah, M., Rodriguez-Couto, S. and Biswas, J., Eds., Elsevier (2022).
91. N. V. Rane, A. Kumari, C. Holkar, D. V. Pinjari and A. B. Pandit, *Sustainable water treatment: Advances and technological interventions*, S. Moulik, A. Mullick, A. Roy Eds., Scrivener Publishing LLC, Beverly (2022).
92. H. M. A. Shahzad, S. J. Khan, M. Khan, H. Schönberger and F.-A. Weber, *Korean J. Chem. Eng.* (2023).
93. R. P. Singh, P. K. Singh and R. L. Singh, *Toxicol. Int.*, **21**, 160 (2014).
94. H. Pan, J. Feng, C. E. Cerniglia and H. Chen, *J. Ind. Microbiol. Biotechnol.*, **38**, 1729 (2011).
95. J. Lin, X. Zhang, Z. Li and L. Lei, *Bioresour. Technol.*, **101**, 34 (2010).
96. W. S. E.-D. Mohamed, *Int. J. Microbiol. Res.*, **7**, 1 (2016).
97. S. Khan and A. Malik, *Can. J. Microbiol.*, **62**, 220 (2016).
98. K. Sarayu and S. Sandhya, *Appl. Biochem. Biotechnol.*, **160**, 1241 (2010).
99. L. Yu, W.-W. Li, M. H.-W. Lam, H.-Q. Yu and C. Wu, *Appl. Microbiol. Biotechnol.*, **95**, 255 (2012).
100. O. Anjaneya, S. Y. Souche, M. Santoshkumar and T. Karegoudar, *J. Hazard. Mater.*, **190**, 351 (2011).
101. A. Das, S. Mishra and V. K. Verma, *J. Biochem. Technol.*, **6**, 962 (2016).
102. H. Modi, G. Rajput and C. Ambasana, *Bioresour. Technol.*, **101**, 6580 (2010).
103. Z. Cai, W. Zhang, J. Ma, J. Cai, S. Li, X. Zhu, G. Yang and X. Zhao, *Water Environ. Res.*, **87**, 516 (2015).
104. S. K. Hubadillah, M. H. D. Othman, Z. S. Tai, M. R. Jamalludin, N. K. Yusuf, A. Ahmad, M. A. Rahman, J. Jaafar, S. H. S. A. Kadir and Z. Harun, *Chem. Eng. J.*, **379**, 122396 (2020).
105. J. Dasgupta, J. Sikder, S. Chakraborty, S. Curcio and E. Drioli, *J. Environ. Manage.*, **147**, 55 (2015).
106. A. Yurtsever, B. Calimlioglu and E. Sahinkaya, *Chem. Eng. J.*, **314**, 378 (2017).
107. H. F. Heiba, A. A. Taha, A. R. Mostafa, L. A. Mohamed and M. A. Fahmy, *Korean J. Chem. Eng.*, **35**, 1844 (2018).
108. E. Sahinkaya, A. Sahin, A. Yurtsever and M. Kitis, *J. Environ. Manage.*, **222**, 420 (2018).
109. D. Jager, D. Kupka, M. Vaclavikova, L. Ivanicova and G. Gallios, *Chemosphere*, **190**, 405 (2018).
110. N. Yousefi, R. Nabizadeh, S. Nasseri, M. Khoobi, S. Nazmara and A. H. Mahvi, *Korean J. Chem. Eng.*, **34**, 2342 (2017).
111. M. Laqbaqbi, M. García-Payo, M. Khayet, J. El Kharraz and M. Chaouch, *Sep. Purif. Technol.*, **209**, 815 (2019).
112. Z. Khani-Arani and A. Akbari, *Korean J. Chem. Eng.*, **39**, 2849 (2022).
113. W. Hua and Y. Kang, *Korean J. Chem. Eng.*, **40**, 1122 (2023).
114. M. Ağtaş, Ö. Yılmaz, M. Dilaver, K. Alp and I. Koyuncu, *J. Clean. Prod.*, **256**, 120359 (2020).
115. R. N. R. Sulaiman, H. A. Rahman, N. Othman, M. B. Rosly, N. Jusoh and N. F. M. Noah, *Korean J. Chem. Eng.*, **37**, 141 (2020).
116. S. Nosrati, K. Seifpanahi-Shabani and M. Karamoozian, *Korean J. Chem. Eng.*, **34**, 2406 (2017).
117. Z. Fallahnejad, G. Bakeri and A. F. Ismail, *Korean J. Chem. Eng.*, **39**, 1902 (2022).
118. H. Hayat, Q. Mahmood, A. Pervez, Z. A. Bhatti and S. A. Baig, *Sep. Purif. Technol.*, **154**, 149 (2015).
119. Y. K. Ong, F. Y. Li, S.-P. Sun, B.-W. Zhao, C.-Z. Liang and T.-S. Chung, *Chem. Eng. Sci.*, **114**, 51 (2014).

120. B. Ramavandi and S. Farjadfard, *Korean J. Chem. Eng.*, **31**, 81 (2014).
121. A. Azizi, M. A. Moghaddam, R. Maknoon and E. Kowsari, *Process Saf. Environ. Prot.*, **95**, 255 (2015).
122. T. M. Mansour, T. M. Ismail, K. Ramzy and M. Abd El-Salam, *Alexandria Eng. J.*, **59**, 3741 (2020).
123. Z. Youcai, *Pollution control technology for leachate from municipal solid waste*, Youcai, Z., Ed., Butterworth-Heinemann (2018).
124. C. Visvanathan, S. Muttamara, S. Babel and R. B. Aim, *Sep. Sci. Technol.*, **29**, 315 (1994).
125. C. Fersi and M. Dhahbi, *Desalination*, **222**, 263 (2008).
126. E. Alventosa-deLara, S. Barredo-Damas, E. Zuriaga-Agustí, M. I. Alcaina-Miranda and M. I. Iborra-Clar, *Sep. Purif. Technol.*, **129**, 96 (2014).
127. T. Chidambaram, Y. Oren and M. Noel, *Chem. Eng. J.*, **262**, 156 (2015).
128. M. Mondal and S. De, *Chem. Eng. J.*, **285**, 304 (2016).
129. H. R. Rashidi, N. M. N. Sulaiman, N. A. Hashim, C. R. C. Hassan and M. R. Ramli, *Desalin. Water Treat.*, **55**, 86 (2015).
130. F. Li, J. Huang, Q. Xia, M. Lou, B. Yang, Q. Tian and Y. Liu, *Sep. Purif. Technol.*, **195**, 83 (2018).
131. N. Mokhtar, W. Lau, A. Ismail, S. Kartohardjono, S. Lai and H. Teoh, *Chem. Eng. Res. Des.*, **111**, 284 (2016).
132. A. K. An, J. Guo, S. Jeong, E.-J. Lee, S. A. A. Tabatabai and T. Leiknes, *Water Res.*, **103**, 362 (2016).
133. J. Lin, W. Ye, M.-C. Baltaru, Y. P. Tang, N. J. Bernstein, P. Gao, S. Balta, M. Vlad, A. Volodin and A. Sotto, *J. Membr. Sci.*, **514**, 217 (2016).
134. Q. Shi, N. Zhang, D. Wang, J. Zhang, Y. Li and Z. Wang, *Desalination*, **551**, 116410 (2023).
135. M. Kaykhaii, M. Sasani and S. Marghzari, *Chem. Mater. Eng.*, **6**, 31 (2018).
136. M. Hossain, I. Mahmud, S. Parvez and H. M. Cho, *Environ. Eng. Res.*, **18**, 157 (2013).
137. H. Lee, S. H. Park, Y.-K. Park, B. H. Kim, S.-J. Kim and S.-C. Jung, *Chem. Cent. J.*, **7**, 1 (2013).
138. J. Bae, N. Park, G. Kim, C. H. Lee, Y.-K. Park and J.-K. Jeon, *Korean J. Chem. Eng.*, **31**, 624 (2014).
139. A. Ali Redha, *Arab J. Basic Appl. Sci.*, **27**, 183 (2020).
140. H. Gupta and P. R. Gogate, *Ultrason. Sonochem.*, **30**, 113 (2016).
141. S. Soroush, N. M. Mahmoodi, B. Mohammadnezhad and A. Karimi, *Korean J. Chem. Eng.*, **39**, 2394 (2022).
142. H. Liu, C. Xu, X. Wei, Y. Ren, D. Tang, C. Zhang, R. Zhang, F. Li and C. Huo, *Water, Air, Soil Pollut.*, **231**, 504 (2020).
143. E. E. Özbaşa, B. Balçıkb and H. Ozcana, *Desalin. Water Treat.*, **172**, 78 (2019).
144. T. Sime, J. Fito, T. T. I. Nkambule, Y. Temesgen and A. Sergawie, *Chem. Africa*, **6**, 667 (2023)
145. C. A. Igwegbe, J. O. Ighalo, K. O. Iwuozor, O. D. Onukwuli and A. G. Adeniyi, *Handbook of porous carbon materials*, A. N. Grace, P. Sonar, P. Bhardwaj, A. Chakravorty, Eds., Springer Nature Singapore, Singapore (2023).
146. M. B. Ceretta, Y. Vieira, E. A. Wolski, E. L. Foletto and S. Silvestri, *J. Water Process. Eng.*, **35**, 101230 (2020).
147. J. M. Rosa, E. B. Tambourgi, R. M. Vanalle, F. M. C. Gamarra, J. C. C. Santana and M. C. Araújo, *J. Clean. Prod.*, **246**, 119012 (2020).
148. L. Bilińska, K. Blus, M. Gmurek and S. Ledakowicz, *Chem. Eng. J.*, **358**, 992 (2019).
149. N. Hien, L. H. Nguyen, H. T. Van, T. D. Nguyen, T. H. V. Nguyen, T. H. H. Chu, T. V. Nguyen, X. H. Vu and K. H. H. Aziz, *Sep. Purif. Technol.*, **233**, 115961 (2020).
150. S. Kortangsakul and M. Hunsom, *Korean J. Chem. Eng.*, **26**, 1637 (2009).
151. G. Asgari, A. Shabanloo, M. Salari and F. Eslami, *Environ. Res.*, **184**, 109367 (2020).
152. O. T. Okareh, T. F. Ademodi and E. O. Igbinosa, *Environ. Monit. Assess.*, **189**, 1 (2017).
153. I. Mironyuk, T. Tatarchuk, M. Naushad, H. Vasylyeva and I. Mykytyn, *J. Mol. Liq.*, **285**, 742 (2019).
154. N. Abdessamad, H. Akrout and L. Bousselmi, *Environ. Technol.*, **36**, 3201 (2015).
155. A. Kumar, G. Sharma, M. Naushad, H. Ala'a, A. García-Peñas, G. T. Mola, C. Si and F. J. Stadler, *Chem. Eng. J.*, **382**, 122937 (2020).
156. P. Kaur, J. P. Kushwaha and V. K. Sangal, *J. Hazard. Mater.*, **346**, 242 (2018).
157. G. S. Arcanjo, A. H. Mounteer, C. R. Bellato, L. M. M. da Silva, S. H. B. Dias and P. R. da Silva, *J. Environ. Manage.*, **211**, 154 (2018).
158. E. GilPavas, I. Dobrosz-Gómez and M. Á. Gómez-García, *J. Water Process. Eng.*, **22**, 73 (2018).
159. S. Zghal, I. Jedidi, M. Cretin, S. Cerneaux, D. Cot, S. Lagerge, S. Deabate and M. Abdelmouleh, *Korean J. Chem. Eng.*, **39**, 2239 (2022).
160. D. Chen, L. Zhao, D. Chen, P. Hou, J. Liu, C. Wang, M. A. Aborisade, M. Yin and Y. Yang, *Chemosphere*, **325**, 138380 (2023).
161. T. Xu, L. Fu, H. Lu, M. Zhang, W. Wang, B. Hu, Y. Zhou and G. Yu, *J. Clean. Prod.*, **401**, 136794 (2023).
162. M. Ječmenica Dučić, A. Krstić, N. Zdolšek, D. Aćimović, B. Savić, T. Brdarić and D. Vasić Anićijević, *Crystals*, **13**, 125 (2023).
163. L. D. Paquini, L. T. Marconsini, L. P. R. Profeti, O. S. Campos, D. Profeti and J. Ribeiro, *Braz. J. Chem. Eng.* (2023).
164. A. Sánchez-Sánchez, M. Tejocote-Pérez, R. M. Fuentes-Rivas, I. Linares-Hernández, V. Martínez-Miranda and R. M. G. Fonseca-Montes de Oca, *Int. J. Photoenergy*, **2018**, 3147923 (2018).
165. D. Gunawan, L. Sapei and L. Riadi, *Environ. Eng. Res.*, **1**, 114 (2018).
166. N. C. Tao and T. L. Luu, *Environ. Eng. Res.*, **28**, 220555 (2022).
167. S. Bener, Ö. Bulca, B. Palas, G. Tekin, S. Atalay and G. Ersöz, *Process Saf. Environ. Prot.*, **129**, 47 (2019).
168. G. Saxena, R. Kishor, S. Zainith and R. N. Bharagava, *Bioremediation for environmental sustainability*, Saxena, G., Kumar, V. and Shah, M. P., Eds., Elsevier (2021).
169. A. Aygun, B. Nas and M. F. Sevimli, *Korean J. Chem. Eng.*, **36**, 1441 (2019).
170. M. Naushad, G. Sharma and Z. A. Alothman, *J. Clean. Prod.*, **241**, 118263 (2019).
171. L. I. Doumic, P. A. Soares, M. A. Ayude, M. Cassanello, R. A. Boaventura and V. J. Vilar, *Chem. Eng. J.*, **277**, 86 (2015).
172. A. Hassani, R. Darvishi Cheshmeh Soltani, M. Kıranşan, S. Karaca, C. Karaca and A. Khataee, *Korean J. Chem. Eng.*, **33**, 178 (2016).
173. K. Hossienzadeh, A. Maleki, H. Daraei, M. Safari, R. Pawar and S. M. Lee, *Korean J. Chem. Eng.*, **36**, 1360 (2019).

174. M. Sheydaei and A. Khataee, *Ultrason Sonochem.*, **27**, 616 (2015).
175. P. K. Rai, V. Kant, R. K. Sharma and A. Gupta, *Eng. Appl. Artif. Intell.*, **122**, 106162 (2023).
176. T. Fazal, A. Razzaq, F. Javed, A. Hafeez, N. Rashid, U. S. Amjad, M. S. U. Rehman, A. Faisal and F. Rehman, *J. Hazard. Mater.*, **390**, 121623 (2020).
177. R. G. Saratale, G. S. Ghodake, S. K. Shinde, S.-K. Cho, G. D. Saratale, A. Pugazhendhi and R. N. Bharagava, *J. Environ. Manage.*, **223**, 1086 (2018).
178. D. M. EL-Mekkawi, N. A. Abdelwahab, W. A. Mohamed, N. A. Taha and M. Abdel-Mottaleb, *J. Clean. Prod.*, **249**, 119430 (2020).
179. A. J. Attia, S. H. Kadhim and F. H. Hussein, *E-J. Chem.*, **5**, 219 (2008).
180. H. Lee, Y.-K. Park and S.-C. Jung, *Korean J. Chem. Eng.*, **39**, 2080 (2022).
181. Y.-S. Cho, H. J. Lee and S. Sung, *Korean J. Chem. Eng.*, **37**, 1071 (2020).
182. M. A. A. Marhalim, S. S. Mohtar, A. M. Mohammed, F. Aziz, M. N. M. Sokri, W. N. W. Salleh, N. Yusof, J. Jaafar, A. F. Ismail, M. Aziz and R. Naim, *Korean J. Chem. Eng.*, **38**, 1648 (2021).
183. N. Bougdour, R. Tiskatine, I. Bakas and A. Assabbane, *Mater. Today: Proc.*, **22**, 69 (2020).
184. K. Sharma, S. Talwar, A. K. Verma, D. Choudhury and B. Mansouri, *Korean J. Chem. Eng.*, **37**, 350 (2020).
185. Y.-O. Kim, H.-U. Nam, Y.-R. Park, J.-H. Lee, T.-J. Park and T.-H. Lee, *Korean J. Chem. Eng.*, **21**, 801 (2004).
186. Y. A. Oktem, B. Yuzer, M. I. Aydin, H. E. Okten, S. Meric and H. Selcuk, *J. Environ. Manage.*, **247**, 749 (2019).
187. W.-L. Wang, H.-Y. Hu, X. Liu, H.-X. Shi, T.-H. Zhou, C. Wang, Z.-Y. Huo and Q.-Y. Wu, *Chemosphere*, **231**, 369 (2019).
188. M. Faghihinezhad, M. Baghdadi, M. S. Shahin and A. Torabian, *Sep. Purif. Technol.*, **283**, 120208 (2022).
189. S. Bakht Shokouhi, R. Dehghanzadeh, H. Aslani and N. Shahmahdi, *J. Water Process. Eng.*, **35**, 101188 (2020).
190. J. Fan, F. Fan, W. Wang, H. Zhang, L. Wang, J. Chang, Q. Liang, D. Wang, Z. Liu and L. Shao, *Chem. Eng. Process.*, **160**, 108296 (2021).
191. K. El Hassani, D. Kalnina, M. Turks, B. H. Beakou and A. Anouar, *Sep. Purif. Technol.*, **210**, 764 (2019).
192. S. P. Ghuge and A. K. Saroha, *J. Water Process. Eng.*, **23**, 217 (2018).
193. R. Rajendran, K. Varadharajan and V. Jayaraman, *Colloids Surf., A Physicochem. Eng. Asp.*, **580**, 123688 (2019).
194. R. Shan, L. Lu, J. Gu, Y. Zhang, H. Yuan, Y. Chen and B. Luo, *Mater. Sci. Semicond.*, **114**, 105088 (2020).
195. J. Guo, S. Khan, S.-H. Cho and J. Kim, *Appl. Surf. Sci.*, **473**, 425 (2019).
196. M. F. Murrieta, I. Sirés, E. Brillas and J. L. Nava, *Chemosphere*, **246**, 125697 (2020).
197. R. Salazar, J. Gallardo-Arriaza, J. Vidal, C. Rivera-Vera, C. Toledo-Neira, M. A. Sandoval, L. Cornejo-Ponce and A. Thiam, *Solar Energy*, **190**, 82 (2019).
198. L. R. Aveiro, A. G. M. Da Silva, E. G. Candido, V. S. Antonin, L. S. Parreira, R. Papai, I. Gaubeur, F. L. Silva, M. R. V. Lanza, P. H. C. Camargo and M. C. Santos, *Chemosphere*, **208**, 131 (2018).
199. N. T. Dung, L. T. Duong, N. T. Hoa, V. D. Thao, L. V. Ngan and N. N. Huy, *Chemosphere*, **287**, 132141 (2022).
200. A. A. Elbatea, S. A. Nosier, A. A. Zatout, I. Hassan, G. H. Sedahmed, M. H. Abdel-Aziz and M. A. El-Naggar, *J. Water Process. Eng.*, **41**, 102042 (2021).
201. A. Ahmadi Zahrani and B. Ayati, *J. Electroanal. Chem.*, **873**, 114456 (2020).
202. M. L. A. Ramalho, V. S. Madeira, I. L. O. Brasileiro, P. C. R. Fernandes, C. B. M. Barbosa, S. Arias and J. G. A. Pacheco, *J. Photochem. Photobiol. A*, **404**, 112873 (2021).
203. M. Tariq, M. Muhammad, J. Khan, A. Raziq, M. K. Uddin, A. Niaz, S. S. Ahmed and A. Rahim, *J. Mol. Liq.*, **312**, 113399 (2020).
204. Y. Li, D. Chen, S. Fan and T. Yang, *J. Taiwan Inst. Chem. Eng.*, **96**, 185 (2019).
205. H. Qian, Q. Hou, G. Yu, Y. Nie, C. Bai, X. Bai and M. Ju, *J. Clean. Prod.*, **273**, 123028 (2020).
206. A. Khataee, P. Gholami and M. Sheydaei, *J. Taiwan Inst. Chem. Eng.*, **58**, 366 (2016).
207. Y. Sun, S. Cheng, Z. Lin, J. Yang, C. Li and R. Gu, *J. Hazard. Mater.*, **384**, 121307 (2020).
208. R. V. Khandare and S. P. Govindwar, *Biotechnol. Adv.*, **33**, 1697 (2015).
209. T. R. Waghmode, M. B. Kurade, R. T. Sapkal, C. H. Bhosale, B.-H. Jeon and S. P. Govindwar, *J. Hazard. Mater.*, **371**, 115 (2019).
210. M. Ahmadi, P. Amiri and N. Amiri, *Korean J. Chem. Eng.*, **32**, 1327 (2015).
211. M. Punzi, F. Nilsson, A. Anbalagan, B.-M. Svensson, K. Jönsson, B. Mattiasson and M. Jonstrup, *J. Hazard. Mater.*, **292**, 52 (2015).
212. T. de Mello Florêncio, K. S. de Araújo, R. Antonelli, A. L. de Toledo Fornazari, P. C. R. da Cunha, L. H. da Silva Bontempo, A. de Jesus Motheo, A. C. Granato and G. R. P. Malpass, *Environ. Sci. Pollut. Res.*, **23**, 19292 (2016).
213. G. Han, C.-Z. Liang, T.-S. Chung, M. Weber, C. Staudt and C. Maletzko, *Water Res.*, **91**, 361 (2016).
214. A. Buthiyappan, R. S. S. Raja Ehsan Shah, A. Asghar, A. A. Abdul Raman, M. A. W. Daud, S. Ibrahim and F. H. Tezel, *Chem. Eng. Commun.*, **206**, 541 (2019).
215. R. Fekri, S.-A. Mirbagheri, E. Fataei, G. Ebrahimzadeh-Rajaei and L. Taghavi, *Anthropog. Pollut.*, **5**, 93 (2021).
216. B. Wang, Y. Liu, H. Zhang, W. Shi, M. Xiong, C. Gao and M. Cui, *J. Ind. Eng. Chem.*, **114**, 33 (2022).