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A Review of Dye Removal Using Polymeric Nanofibers by Electrospinning as Promising Adsorbents

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Abstract

Water is the most important material that humans and creatures need, and water contamination caused by chemicals such as dyes has brought many problems. Various methods have been used to remove dyes as organic contaminants. Polymeric nanofibers prepared by electrospinning have a nanostructure with a high adsorption capacity for removing water contaminants. To solve this problem, the adsorption process is used, which is very effective for removing water pollutants. The adsorption process is very important in terms of expense and reuse. The use of natural polymers is being promoted as a suitable alternative to synthetic polymers and to reduce environmental pollution. The results indicate that preparing nanofibers by electrospinning and using them as adsorbents is a suitable method to remove contaminants. The effect of operational parameters on the adsorption removal ability of polymeric nanofibers, the optimal adsorption conditions, and the mechanism of dye adsorption have been investigated in detail. The data indicated that polymeric electrospinning nanofibers can be used as environmentally friendly and effective adsorbents for removing water contaminants. Also, the treated dye wastewater is reused in the dyeing process and is not discharged into the environment to conquer the water shortage.

Keywords: Nanofibers, Dyes, Adsorption, Polymer Nanocomposites, Electrospinning.

1. Introduction

Water pollution has many concerns with industrial activity and population growth. These concerns have diminished over time and owing to the increment in the volume of wastewater and its evacuation in water systems, it has become a global concern. Dye wastewater is one of the most dangerous wastewaters that causes water pollution by changing its properties (Asefi et al., 2010; Wang et al., 2015; Tkaczyk et al., 2020; Lin and Chen, 1997; Varjani et al., 2020; Ayodhya and Veerabhadram, 2018; Mo et al., 2008; Kausar et al., 2018; Tavakoli et al., 2017).

It usually originates from different industries such as textiles, paper, food, plastic, etc. Annual dye production is estimated at 0.7 million tons, and 10-15% of the dye is discharged into the environment as wastewater, which is about 200 million liters per year (Yagub et al., 2014; Gharanjig et al., 2008; Ray et al., 2016; Xue et al., 2019; Wang et al., 2016; Islam et al., 2019; Jiang et al., 2020; Najafi and Frey 2020).

The discharge of colored wastewater in aqueous media and reducing the penetration of sunlight causes many problems for living organisms. To avoid these problems, the dye wastewater must be treated before being discharged into the environment. In recent years, researchers have tried to develop different methods to remove dyes from wastewater such as chemical degradation, biodegradation, coagulation, advanced oxidation, membranes, and adsorption (Davarpanah et al., 2009; Mahmoodi and Mokhtari-Shourijeh, 2017; Mahmoodi et al., 2006; Mohajershojaei et al., 2015; Nasrollahi et al., 2018; Ranjbar-Mohammadi et al., 2010).

Among the above-mentioned procedures, the adsorption process is recommended due to its simplicity and availability. The adsorption process significantly depends on the properties and expense of the adsorbent. Most efforts have been concentrated on the production of highly effective and cheap adsorbents (Mahmoodi, 2013, 2015; Mahmoodi and Arami, 2008, 2009). With the advancement of nanotechnology, different nanomaterials were used as promising and effective adsorbents and substitutes for conventional absorbents. Among these nanomaterials, electrospun polymeric nanofibers have gained considerable attention from many researchers, not only in the field of water treatment but also in other fields in the last two decades. More than 100 natural and synthetic polymers can be converted into electrospun polymeric nanofibers by dissolving them in suitable solvents and spinning them. Polymeric nanofibers have unique properties such as high surface area, high surface-to-volume ratio, and porosity (Fig. 1). Also, they have high adsorption sites and adsorption capacity. These properties allow it to be used as an effective adsorbent for various pollutants such as dyes and other contaminants. The nanofibers have some limitations such as low stability in harsh experimental conditions. To date, some research has been conducted using electrospun polymeric nanofibers in water treatment for dye removal.

In this review, the application of nanofibers for removing dyes from wastewater was studied in detail. Some of the electrospun polymeric nanofibers are used as adsorbents and filters for organic contaminant adsorption, as sensors for pollutant detection, or as catalysts for pollutant degradation. Recently, electrospun polymeric nanofiber was investigated in water treatment for heavy metal removal. The adsorption potential and initial problems of their use as adsorbents for dyes have been discussed in detail (Abrigo et al., 2014; O' Leary et al., 2020; Deitzel et al., 2001; Baumgarten et al., 1971; Megelski et al., 2002; Huang and Thomas, 2020; Li and Wang, 2013; Bhardwaj and Kundu, 2010; Wang and Kumar, 2006; Zhang et al., 2005).

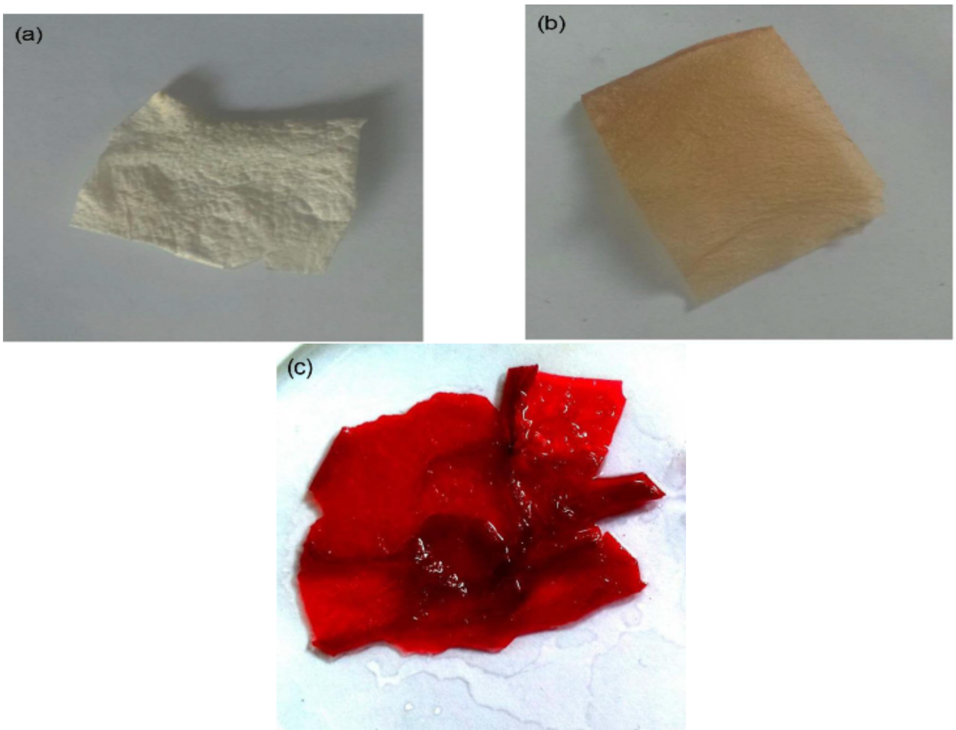


Fig. 1. The images of a) PVA-chitosan, b) PVA-chitosan crosslinking, and c) dye-adsorbed blend nanofiber nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

1.1. Composite

Composites are man-made or natural solids that combine different materials, each with physical or chemical procedures that make them superior to materials made from raw materials. Production of raw materials is achieved when creating new materials and creating a specific final structure. Composites are usually designed to provide a vast range of properties and characteristics, including stiffness and strength, ease of fabrication in complex shapes, ease of repair of damaged structures, and corrosion resistance (Pillay et al., 2013; Fong et al., 1999; Zong et al., 2002).

1.2. Nanomaterials

Nanomaterials (Fig. 2) are classified based on dimensions and materials. To classify nanomaterials based on their dimensions, nanomaterials can be classified as zero-dimensional (0D) for all outer dimensions and the nanoscale is between 1-100 nm (Doshi and Reneker, 1995). Quantum dots, semiconductor nanocrystals with dimensions less than 10 nm act as an electrical potential and are used to store electrons and holes in electronic devices. At the nanoscale, one-dimensional (1D) nanomaterials have two outer dimensions and the third is usually micro-scale. These include nanofibers, nanotubes, nanowires, and nanotubes (Luzio et al., 2014).

2. Nanofibers

Sample extraction is necessary for the pre-treatment step. Nanofibrous materials have a high potential for extracting samples before the analytical process. The high adsorption capacity of nanofiber owing to its high surface-to-volume ratio can provide different polymers that are processed in nanofibers to study different chemical interactions. The history of nanofibers is shown in Table 1 and the classification of nanofibers is shown in Fig. 3 (Agarwal et al., 2009).

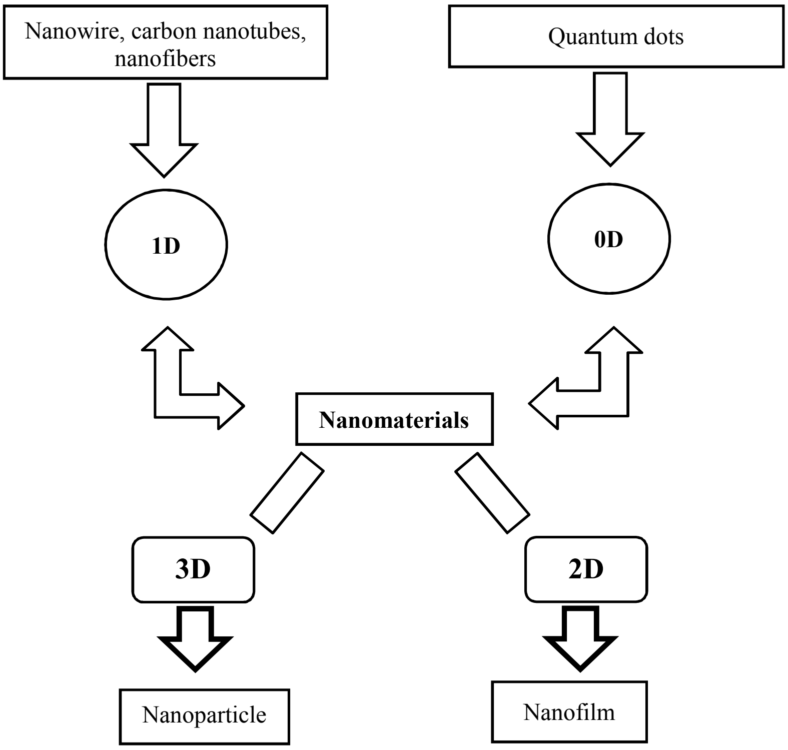


Fig. 2. Various nanomaterials with different dimensions

Table 1. History of the development of nanofiber materials

Year	Nanofiber materials
2014-2020	Polyamide nanofibers
2015-2020	Electrospinning of nanofibers by a sol-gel procedure
2016-2020	Magnetic nanocomposite fiber
2017-2020	Polystyrene coated nanofibers
2018-2020	Combination of electrospinning and melting technology
2019-2020	Nanofiber-based graphene

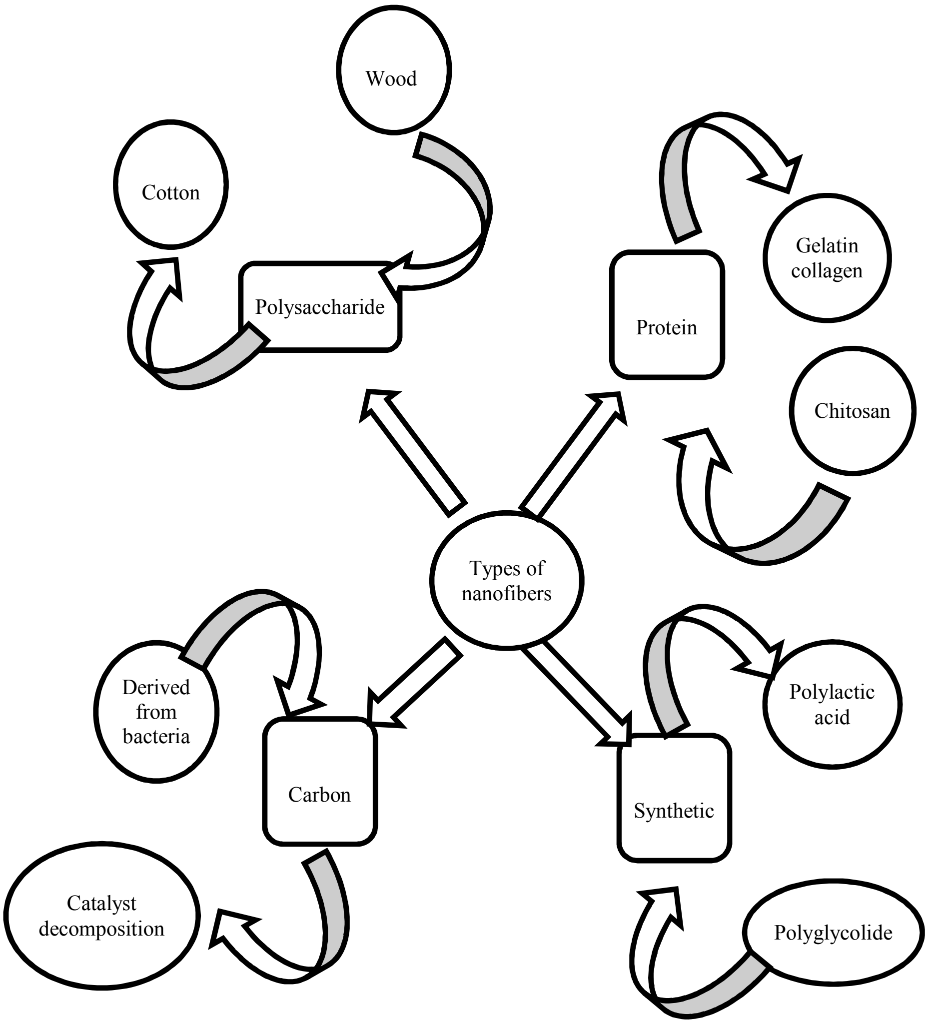


Fig. 3. Classification of nanofibers (Agarwal et al., 2009)

2.1. Nanofiber electrospinning production process

Electrospinning is the best procedure for preparing nanofibers because it is simple, amenable, and low-cost. In the electrospinning process, a high voltage is used for the liquid polymer and a continuous jet is emitted from the electrospinning machine and collected by a collector. The surface tension of polymer droplets is overcome by an applied electric field. The droplets then expand in a cone shape called a "Taylor cone" and are pulled out of the cone to shape a fiber jet. The solvent in the nozzle evaporates in the atmosphere as the fiber nozzle moves, and the solid polymer fibers stick to the metal collector. Based on the polymer manufacturing process, electrospinning processes can be divided into two groups that include solution and molten electrospinning.

The disadvantages of solution electrospinning are low efficiency, highly solvent extraction processes, and the need for poisonous solvents. Many concerns about melt electrospinning led researchers to describe it as melt electrospinning owing to the inherent difficulty in forming finer fibers, high viscosity polymer melts, and high voltage discharges. Studies present that a needleless and nozzle-less process has been proposed to increment the efficiency of solution electrospinning.

Electrospinning, the process of forming nanofibers from solution or melting of polymers with an electrostatic field, is very important. A typical electrospinning device, also called needle electrospinning, consists of nanofibers on a collector. It can be used in any lab to perform basic experiments such as finding suitable polymers, solvents, concentration, humidity, and temperature. After preliminary tests, more efficient electrospinning procedures such as multi-jet electrospinning and needleless electrospinning are recommended (Table 2).

Needleless electrospinning nozzles are formed directly from the free surface of the polymer. In this way, a multi-point composite nozzle with higher output and higher efficiency is obtained compared to single-needle electrospinning, and unlike multi-nozzle electrospinning, no problem is observed in the use of the nozzle. A special type of electrospinning is the so-called sol-gel, which is mainly used to produce inorganic nanofibers, for example by calcination. However, inorganic fibers are very fragile and their fibrous structure can only be observed with a scanning electron microscope. Electrospinning produces very fine nanofibers. But owing to the very small diameter, these fibers are not stable and the composite formed by nanofibers collapses. So, the product of electrospinning technology is a (2D)-dimensional fabric. Another fiber production technique that can be used to produce polymeric fibers is melt-blowing.

This procedure is less common than electrospinning in producing fibers for analytical applications. During the melt-blowing process, the molten polymer is drawn through the mold and filaments, usually at the same temperature as the molten polymer, and passed through a stream of hot air. This technique allows the production of very thin fibers with a diameter of less than a micron and the production of materials with a more porous (3D)-dimensional structure than the nanofiber sheets produced by electrospinning (Zander, 2013; Sun et al., 2014).

Table 2. Types of electrospinning

Number	Electrospinning
1	Single needle
2	Double-needle
3	Multi-needle
4	No needle
5	Bubble
6	Blown bubble spinning
7	Coaxial
8	Emulsion

2.2. Effect of parameters on electrospinning

Different parameters can affect electrospinning (Fig. 4). These parameters are classified as electrospinning parameters, solution parameters, and environmental parameters. Several factors such as conductivity, rheological properties of the spinning dope, surface tension, air flow rate, temperature, and humidity affect the electrospinnability as the ability of a polymer solution to be electrospun into fibers (Angel et al., 2020; O'Connor et al., 2021).

The electrospinning process includes the applied electric field, the distance between the needle and the collector, the flow rate, and the diameter of the needle. Solution parameters include solvent, polymer concentration, viscosity, solution conductivity, water content, and temperature. These parameters directly affect the production of electrospun fibers. So, these parameters are needed for a better understanding of the electrospinning procedure and the fabrication of polymeric nanofibers (Zander, 2013; Sun et al., 2014).

3. Types of polymers for nanofibers

3.1. Synthetic polymers

Synthetic polymers are man-made polymers that are often derived from crude oil. From the application point of view, thermoplastics, elastomers, and synthetic fibers are divided into three main categories. They are commonly found in various products around the world. Different synthetic polymers with variations in side chains are available. Common synthetic polymers such as polyethylene, polystyrene, and polyacrylate are composed of carbon-carbon bonds, while polymers with heterogeneous chains such as polyamides, polyesters, polyurethanes, polysulfides, and polycarbonates contain other elements such as oxygen, sulfur, and nitrogen.

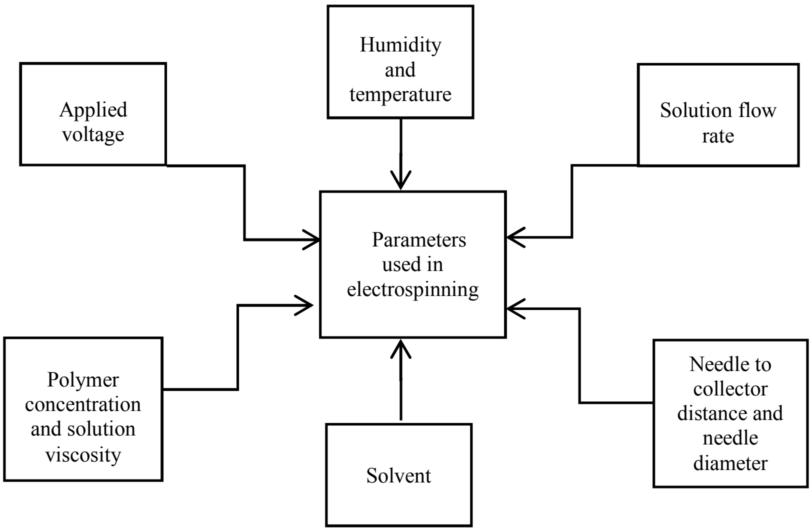


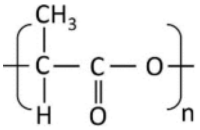
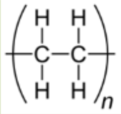
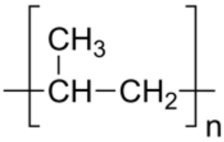
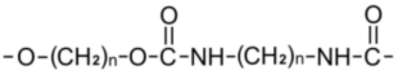
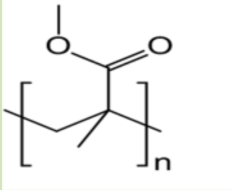
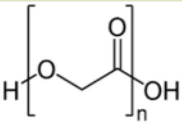
Fig. 4. Effective factors of parameters used in electrospinning

Synthetic polymers include nylon in fibers and polyvinyl chloride in pipes. Regular polyethylene terephthalate bottles are made using polyethylene terephthalate. However, owing to the environmental concerns of these mostly non-biodegradable and synthetically produced synthetic polymers, alternatives such as biopolymers are also being investigated. Table 3 shows the types of synthetic polymers used in electrospinning (Angammana and Jayaram, 2011; Zhang et al., 2006; Megelski et al., 2002; Jarusuwannapoom et al., 2005; Huan et al., 2015; Pelipenko et al., 2013; Park and Lee, 2010; Vrieze et al., 2009; Bae et al., 2013; Wang et al., 2012; Oh and Lee, 2013; Bagheri et al., 2014; Babu et al., 2013).

3.2. Natural polymers

Natural polymers (Table 4) present different structures and physico-chemical properties and can offer different opportunities for biomedical applications owing to their different characteristics, the most important of which are biodegradability. Also, natural polymers have many functional groups that are available for chemical and enzymatic reactions with other molecules, resulting in a variety of biomaterials with suitable structures and properties. They are obtained from plants, mammals, earthworms, and spiders. In addition, some microorganisms can synthesize many biopolymers (Hoogsteen et al., 1990; Yun and Jang, 2014; Sobieraj and Rimnac, 2009; Lin, 2012; Ortel, 1994; Gunatillake et al., 2006; Mikos et al., 1993; Licari, 2004; Yannas, 2004; Aravamudhan et al., 2014; Anitha et al., 2014; Campo et al., 2009; Lundin and Hermansson, 1995; Turquois et al., 1992; Corre et al., 2010; Ullah et al., 2016; Kayra and Aytekin, 2019; Hynninen et al., 2019; Sun et al., 2019; Alishahi and Aider, 2012; Kaewklin et al., 2018; Zhang et al., 2019; Augst et al., 2006; Jeon et al., 2010; Andersen et al., 2015; Jeon et al., 2012; Sande, 2005; Mohnen, 2008; Maxwell et al., 2012; Einhorn-Stoll et al., 2014; Liang et al., 2012).

Table 3. Types of synthetic polymers used in electrospinning

Structure	Synthetic polymer	Ref.
	Polylactic acid	(Angammana and Jayaram, 2011; Zhang et al., 2006; Megelski et al., 2002; Jarusuwannapoom et al., 2005)
	High molecular weight polyethylene	(Huan et al., 2015; Pelipenko et al., 2013)
	Polypropylene	(Park and Lee, 2010)
 $-O-(CH_2)_n-O-\overset{O}{\overset{\Vert}{C}}-NH-(CH_2)_n-NH-\overset{O}{\overset{\Vert}{C}}-$	Polyurethane	(Vrieze et al., 2009; Bae et al., 2013)
	Poly (methyl methacrylates)	(Wang et al., 2012)
	Polyglycolide	(Oh and Lee, 2013; Bagheri et al., 2014; Babu et al., 2013)

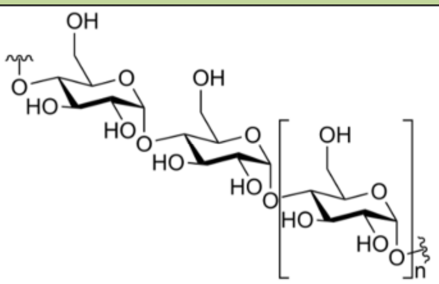
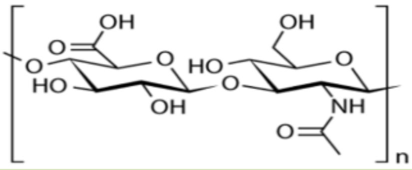
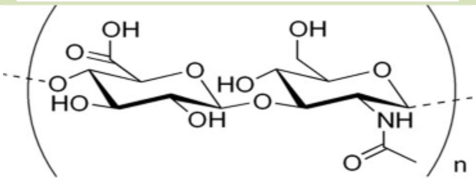
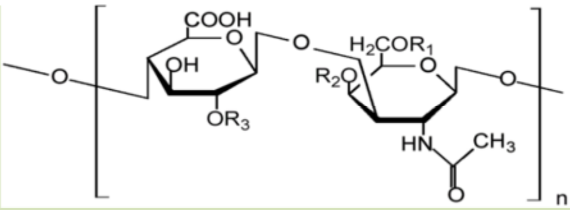
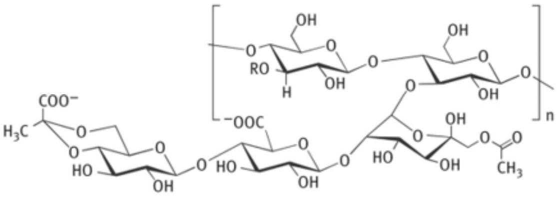
4. Application of nanofibers in wastewater treatment

As shown in Fig. 5, nanofibers can be used for removing different pollutants such as dyes, heavy metal ions, hydrocarbons, pesticides, drugs, etc. In this review, dye removal by nanofibers was investigated in detail.

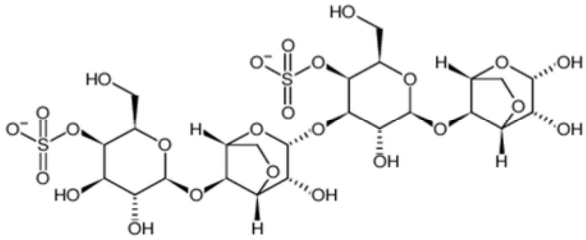
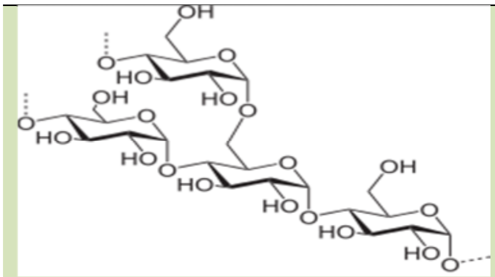
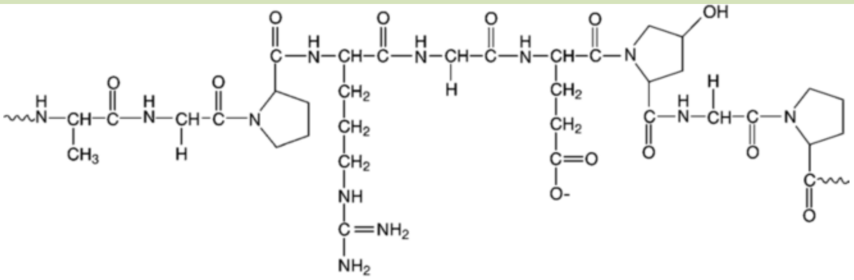
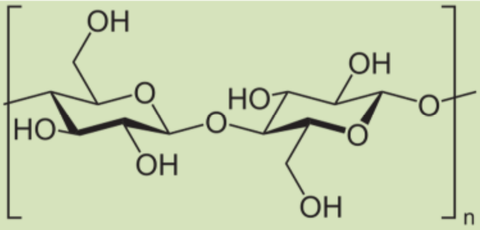
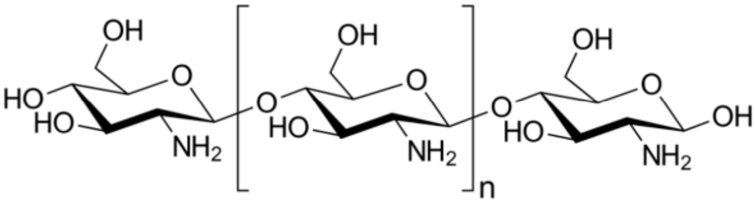
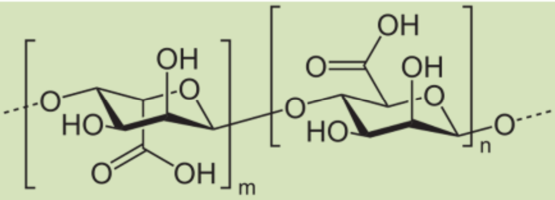
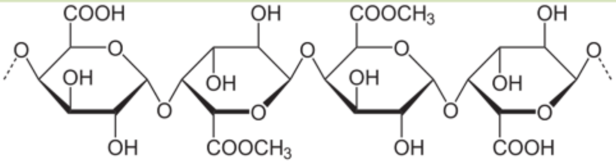
4.1. Removal of dyes from wastewater

Treatment of dye (Fig. 6) containing wastewater has become an important process for many environmental issues. The demand for effective methods of removing dyes from wastewater is increasing day by day, and various adsorbents are available for this purpose. Among several advanced adsorbents, nanofibers can be considered a novel generation of materials that offer significant advantages for applications in removing contaminants from wastewater. Moreover, the synthesized nanofibers using metal oxides such as titanium dioxide, zinc oxide, and zirconium dioxide have demonstrated the ability to mineralize organic pollutants. These proprietary nanofibers generate hydroxyl radicals that can destroy contaminants and remove them in wastewater. A polysaccharide-based hydrogel was designed to remove methylene blue dye. A good method to increment efficiency is the encapsulation of titanium dioxide (Titania) nanoparticles. By adding Titania to cellulose nanofibers, a material to remove methylene blue in wastewater by adsorption and photocatalysis can be obtained. Acrylic acid/graphene oxide carboxylate is prepared by electrospinning for removing dyes from wastewater. The prepared composite nanofibers presented high efficiency in dye adsorption compared to

Table 4. Types of natural polymers used in electrospinning

Structure	Natural polymers
	Polysaccharides
	Glycosaminoglycans
	Hyaluronic acid
	Chondroitin sulfate
	Xanthan gum

cont. Table 4. Types of natural polymers used in electrospinning

Structure	Natural polymers
	Caraginan
	Starch
	Gelatin
	Cellulose
	Chitosan
	Alginic acid
	Pectin

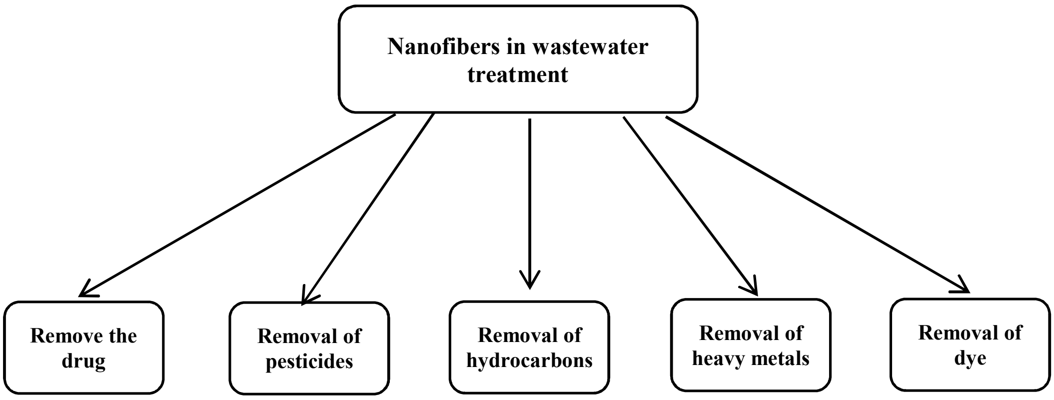


Fig. 5. Nanofibers for removing different pollutants

other adsorbents (Sriamornsak, 2011; Braccini and Perez, 2001; Xu et al., 2018; Xu et al., 2014; Chan and Choo, 2013; Meersman et al., 2017; Wicker et al., 2014; Cai et al., 2020).

In the textile industry, after the dye is used for dyeing the material, colored wastewater is usually considered industrial waste. Industries must take suitable treatment methods before discharging colored wastewater into the environment. Water contamination caused by dyes is unacceptable for environmentalists and the general public concerns because it is poisonous and dangerous. After the dyeing process, the pH of the solution may be acidic at high temperatures. The mechanism of oxygen transfer and water cleaning is disturbed by this phenomenon. These wastewaters are released into the environment after use and menace ecosystems by contaminating water sources that prevent the use of water.

When natural water sources are contaminated with dyes, they produce foul odors and cause eye pain in humans. The wastewater from aquatic plants and animals can also harm terrestrial organisms. Mixing colored wastewater with water sources owing to the low density in the wastewater with an amount of 0.8 kg/m^3 increments the turbidity of the water and the water density of 1 kg/m^3 creates a visible layer on the surface of the water and prevents the penetration of sunlight in the aquatic systems. It becomes necessary to carry out processes such as photosynthesis and respiration. In the next stage, when the colored wastewater flows into the forests and fields, it affects the soil. By blocking the pores of the soil, the quality of water reduces and makes it unsuitable for daily use and consumption, which causes the growth of bacteria and viruses. Animals that use this water source suffer from a lack of clean drinking water.

Villagers and nomads who depend solely on rivers are deprived of water sources or worse, become ill from unknowingly consuming contaminated water. Dissemination of dyes in the environment slowly destroys the environment and endangers human health. Skin contact with colored wastewater can cause skin irritation. Eye burns and permanent eye damage can occur in animals and humans alike when colored wastewater comes in contact with the human eye.

Chemicals in colored wastewater that are poured into water sources evaporate in the environment and can cause shortness of breath and respiratory problems if inhaled. Consumption of dyes can cause high sweating, confusion, methemoglobinemia, mouth burning, nausea, or vomiting. Therefore, it is important to treat wastewater containing hazardous dyes to prevent harmful effects on water, animals, and humans. Environmental disposal of colored wastewater has received little attention so far. It is only with the increment in health problems in the last 30 years that this issue has received attention. Then we looked for information about the dyes, their uses, and how to remove them to find solutions. These solutions are implemented by dye manufacturers, the dye processing industry, and even by the government.

Recently, environmental legislators have enacted laws regarding the presence of poisonous and colored wastewater in water bodies. According to this rule, the dye processing industry must ensure that the wastewaters from their factories meet the wastewater discharge quality standards adopted by the International Dyeing Industry from the Zero Discharge Program for Hazardous Chemicals. Textile wastewaters rich in contaminants such as biologically required oxygen, chemically required oxygen, dyes, poisonous chemicals, soluble salts, pH, suspended solids, and colored wastewaters should be less than the specified limit.

Industries that produce colored wastewater must deal with the damage it causes to the environment and organisms. The treated dye wastewater is reused in the dyeing process and is not released into the environment. Buying and even using fresh water in the dyeing process is an economical idea. Fresh water is not cheap enough for dyes and expense reduction is usually a desirable factor for all industries (Azami et al., 2012; Fazaeli et al., 2015; Tian et al., 2011; Zeng et al., 2017; Rauf and

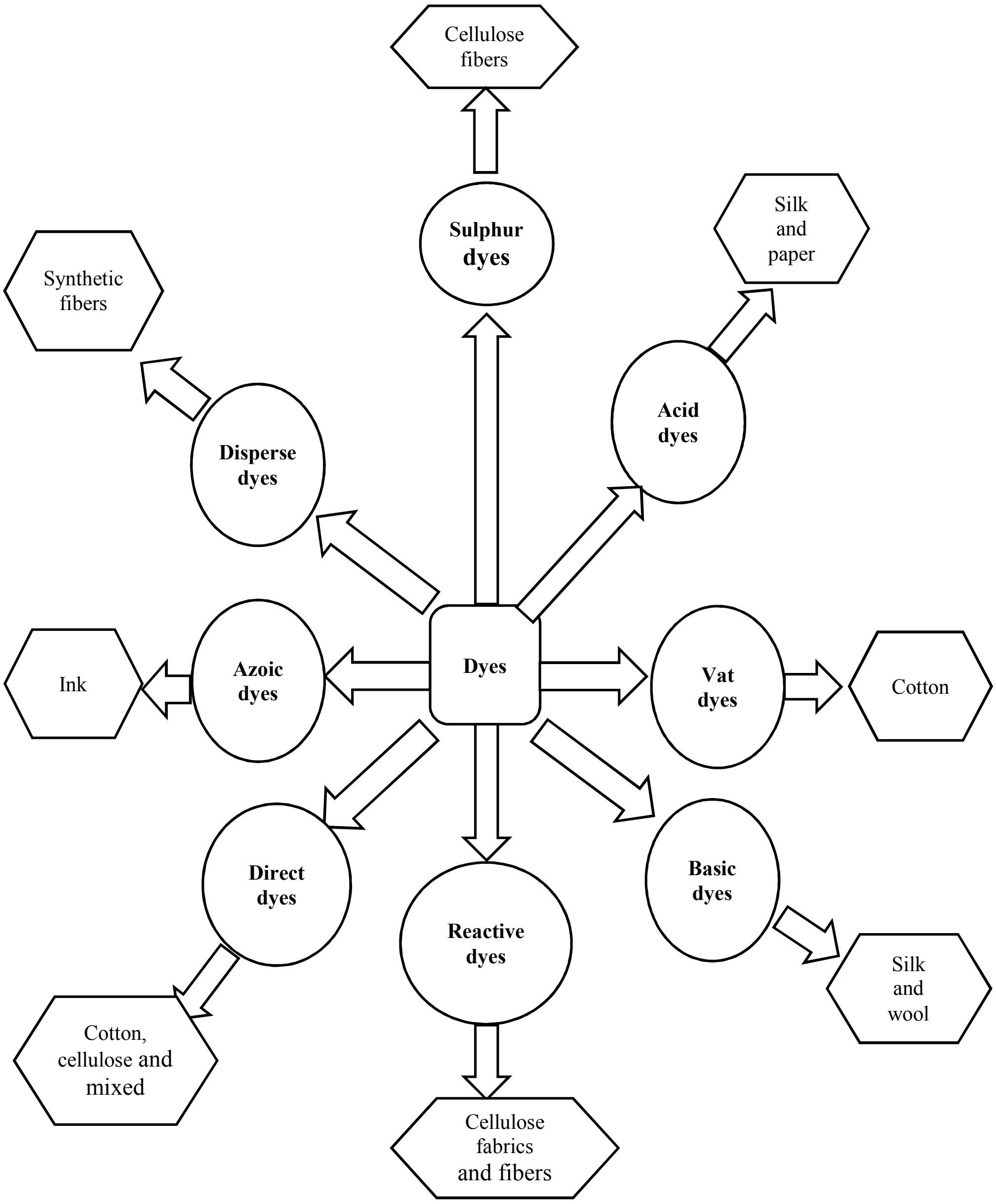


Fig. 6. Classification of dyes

Ashraf, 2012; Crini, 2006; Dos Santos et al., 2007).

4.2. Removal of dye procedure

Currently, several studies are being conducted to find a process to remove the dye that can be recycled and reused.

Existing dye removal methods can be divided into three categories: biological, chemical, and physical methods (Fig. 7).

Many dye removal methods have been investigated in the last 30 years, but due to the limitations of most of the methods, few of them are used in the relevant industries today (Nguyen and Juang, 2013; Srinivasan and Viraraghavan, 2010; Gisi et al., 2016).

5. Dye adsorption process: adsorbents and operational parameters

Adsorption is one of the high-quality wastewater treatment procedures to remove water-soluble organic contaminants such as dyes. It is obtained from the accumulation of substances on the surface of a solid. When a solution containing an adsorbent comes in contact with a solid that has a highly porous surface structure, the intermolecular attraction between the liquid and the solid causes the solute to sit on the surface (Mezohegyi et al., 2012).

Fig. 8 presents the types of adsorbents including zeolites, coal, clay, ore, and other materials. Adsorbents can be made from used waste sources including coconut shells, rice husk, petroleum waste, tannin-rich materials, sawdust, fertilizer waste, sugar industry waste, blast furnace slag, chitosan, seafood processing waste, seaweed, and algae. Table 5 presents the comparison of different adsorbents in terms of dye adsorption capacity (Sarro et al., 2018; Tang et al., 2018; Yagub et al., 2014; Saratale et al., 2011; Pan et al., 2017; Rodrigo, 2021; Akduman et al., 2017). Also, Table 6 presents the characterization of various polymeric adsorbents used for removing dyes.

The pH of the solution has a great effect on the adsorption process. The removal of dyes in Fig. 9 shows that the adsorption capacity increases with a reduction in pH, and its amount is pH = 2.1. Considering the functional groups, there is an electrostatic attraction between the positively charged nanofiber and the anionic dye molecules. Increasing the pH cause reductions in the number of positively charged sites on the nanofibers. Fig. 10 shows the effect of adsorption contact time on dye removal. The decrease in dye adsorption is attributed to the adsorption site and accumulation of dye molecules on the surface of the adsorbent, and the repulsive forces between the dye molecules on the adsorbent. The effect of adsorbent dosage on dye removal by the nanofibers is shown in Fig. 11. The removal of dyes increases to a certain extent with the increment of the adsorbent dose, and after that, it reaches a certain amount, which increments the surface of the adsorbent and the availability of adsorption sites. With the increase of nanofiber dose, the number of active sites (NH_2) on the surface of nanofibers increments. The effect of the initial concentration of dyes is shown in Fig. 12. The results showed that the removal of dye decreases with the increase of the dye concentration, and if the amount of adsorbent is constant, the initial concentration of the dye on the adsorbent increases (Nethaji et al., 2013; Wawrzkiewicz et al., 2019).

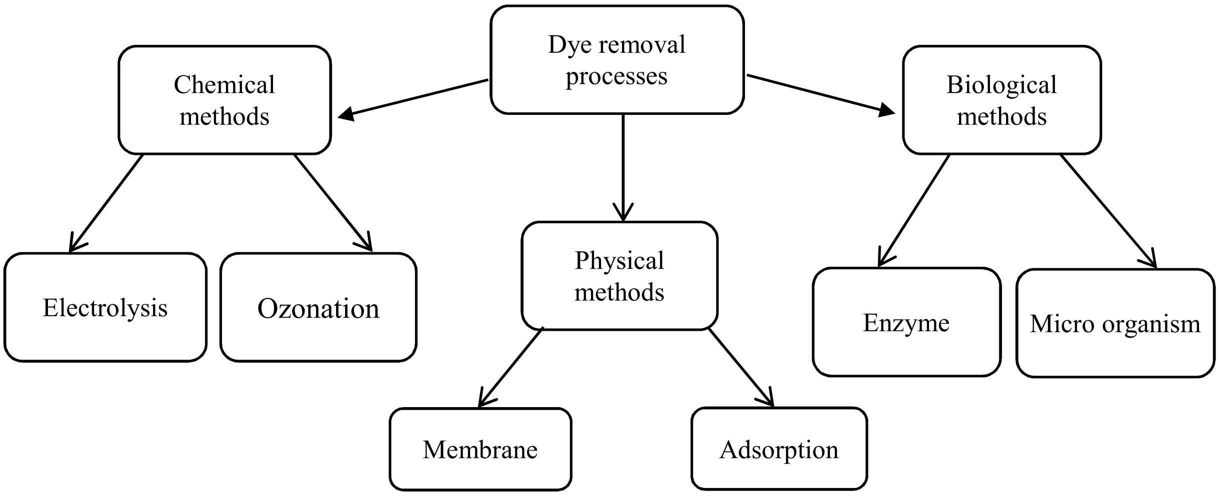


Fig. 7. Treatment methods for removing dyes from wastewater

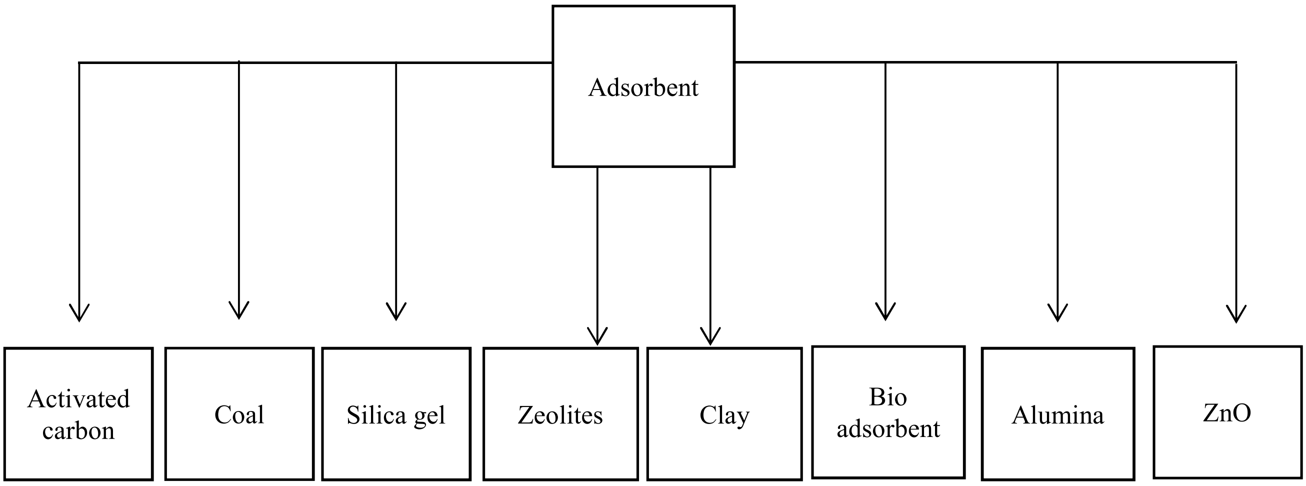


Fig. 8. Type of adsorbents

Table 5. Comparison of different adsorbents in dye adsorption and surface adsorption capacity

Adsorbent	Dyes	Adsorption capacity	Ref.
Polyvinyl alcohol nanofibers	Reactive Red 141	88.31 mg/g	(Sarro et al., 2018)
Polyurethane nanofibers	Reactive Red 141	14.48 mg/g	(Tang et al., 2018)
Polyacrylonitrile/β-cyclodextrin nanofibers	Methylene Blue	108.66 mg/g	(Yagub et al., 2014)
Polyacrylonitrile/graphene oxide nanofibers grafted with chitosan	Yellow Sunset	211.54 mg/g	(Saratale et al., 2011)
TEMPO-oxidized cellulose nanofiber	Brilliant Blue	162 mg/g	(Pan et al., 2017)
Polyvinyl alcohol nanofibers containing diethylenetriamine and ethylenediamine in the presence of glutaraldehyde	Direct Blue 78	400 mg/g	(Rodrigo, 2021)
Zein/MoS_2 polylactic acid fiber membrane	Methylene Blue	111.20 mg/g	(Akduman et al., 2017)

Table 6. Characterization of different polymeric adsorbents of dyes

Adsorbent	Dyes	Characterization	Ref.
Polyacrylonitrile/ β-cyclodextrin nanofibers	Methylene Blue	Elemental analysis (X-ray energy diffraction spectroscopy) Analysis of determination of the special level X-ray diffraction Scanning electron microscope analysis	(Sun et al., 2021)
Polyvinyl alcohol nanofibers with diethylenetriamine and ethylenediamine in the presence of glutaraldehyde	Direct Red 23, Direct Blue 78	Scanning electron microscope analysis Fourier transform infrared analysis	(Al-Ahmed et al., 2020)
Polylactic acid fiber membrane with Zein/MoS_2	Methylene Blue	Fourier transform infrared analysis X-ray diffraction Scanning electron microscope analysis Atomic force microscope Modeling analysis (WCA)	(Mahmoodi et al., 2017)

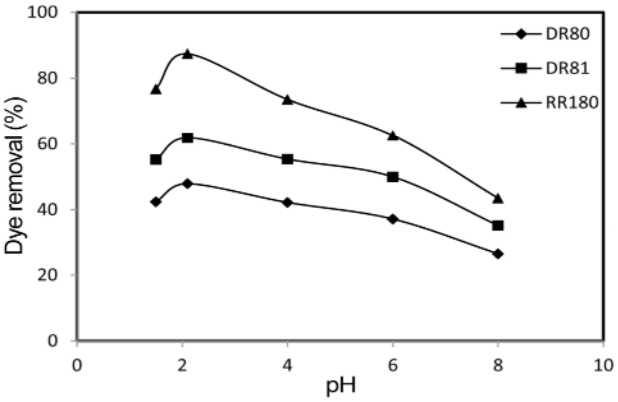


Fig. 9. The effect of solution pH on dye removal by the nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

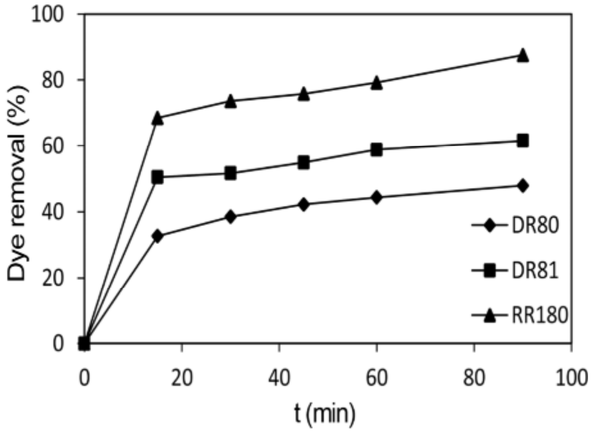


Fig. 10. The effect of contact time on dye removal by the nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

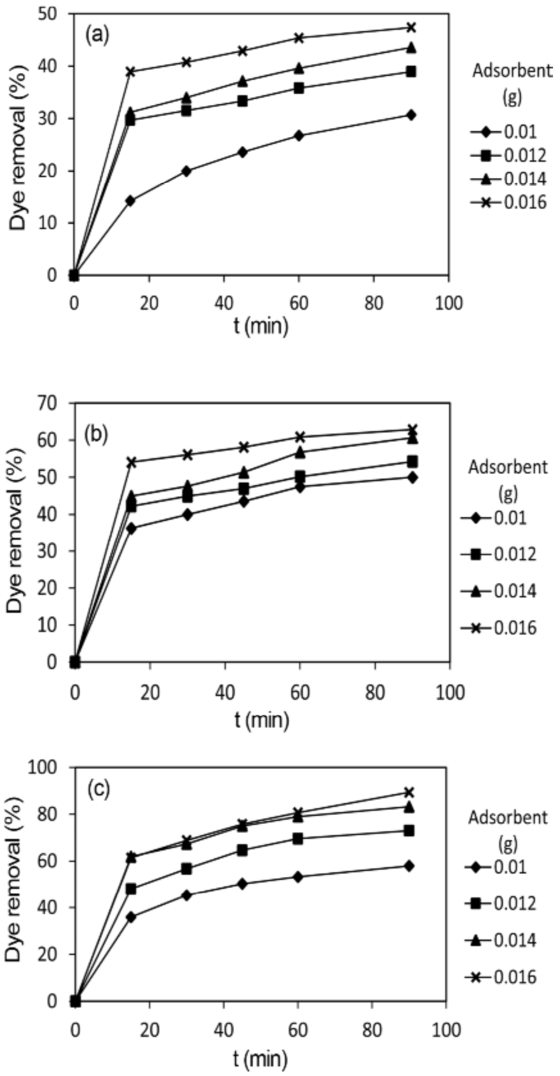


Fig. 11. The effect of adsorbent dosage on dye removal by the nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

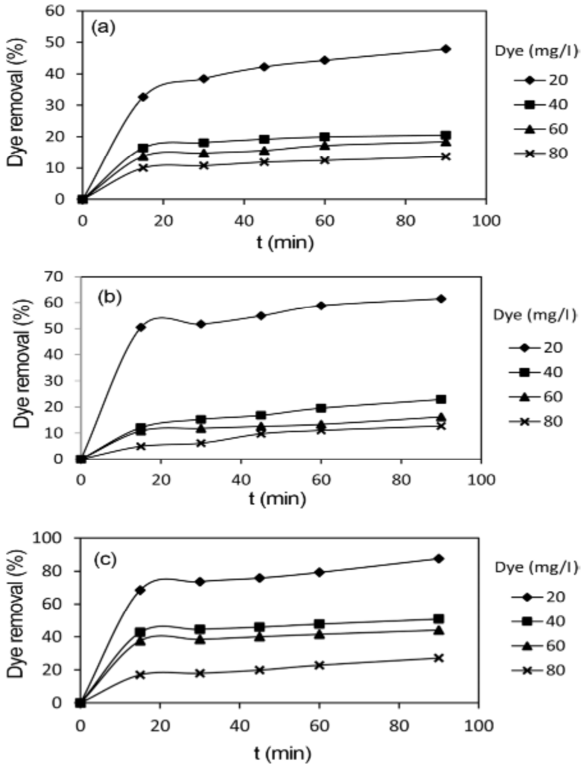


Fig. 12. The effect of initial dye concentration on dye removal by the nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

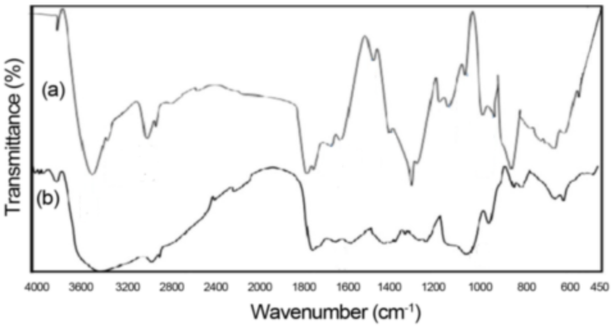


Fig. 13. FTIR spectra a) PVA-chitosan and b) PVA-chitosan crosslinked (Mahmoodi and Mokhtari-Shourijeh, 2015)

6. Characterization of nanofibers

FTIR spectrum of PVA-chitosan is shown in Fig. 13. The peak at 3440.1 cm^{-1} determines the amount of -OH and -NH$_2$ and peaks of 1022.2 and 1447.8 cm^{-1} determine the amount of -C-O. The peak at 1636.8 cm^{-1} is due to the stretching vibrations of water molecules. The peaks at 892.3 and 1100.6 cm^{-1} are related to the structure of chitosan. A peak at 1022.2 cm^{-1} demonstrates C-O and 1650 cm^{-1} presents $C{=}N$ due to the reaction between the amino group of chitosan and the aldehyde group of glutaraldehyde.

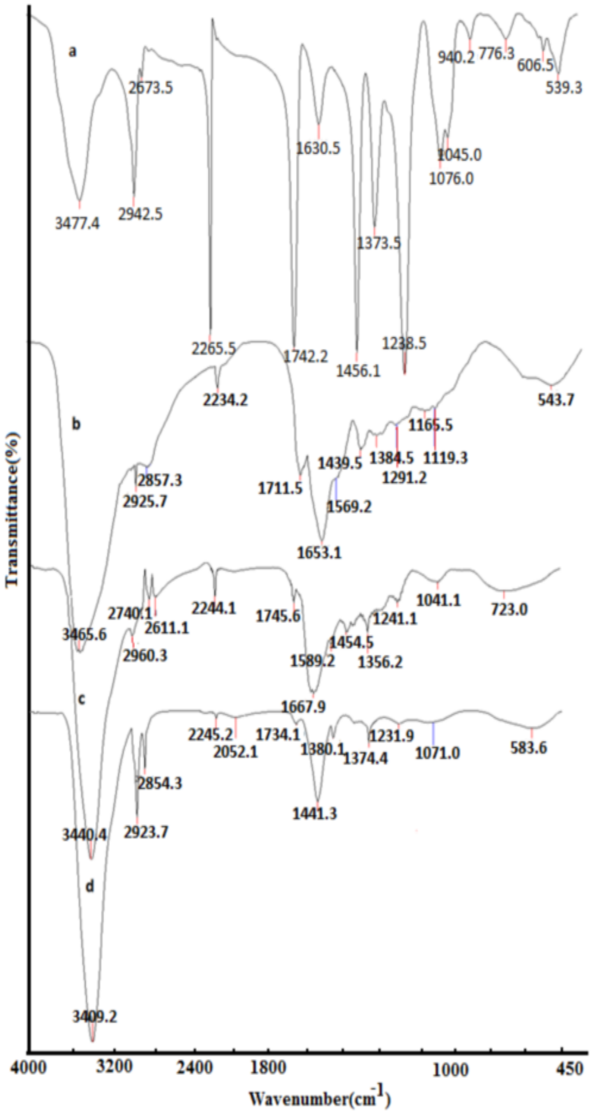


Fig. 14. FTIR spectra of (a) untreated PAN nanofiber b) PAN-15%w/w EDA nanofiber, c) PAN-25%w/w EDA nanofiber, and d) PAN-35%w/w EDA nanofiber (Almasian et al., 2015)

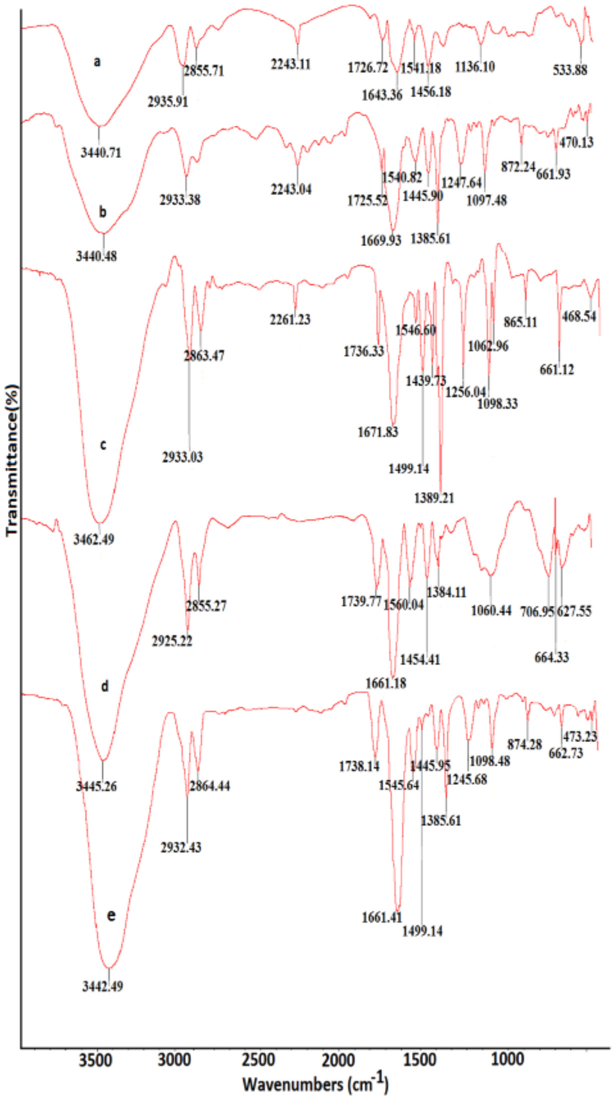
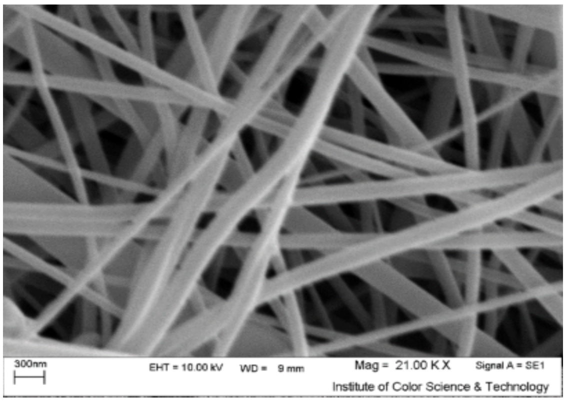
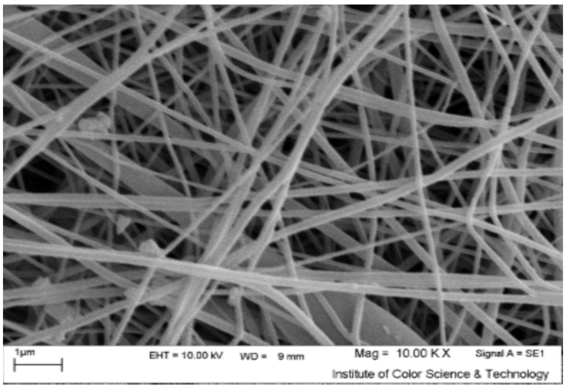


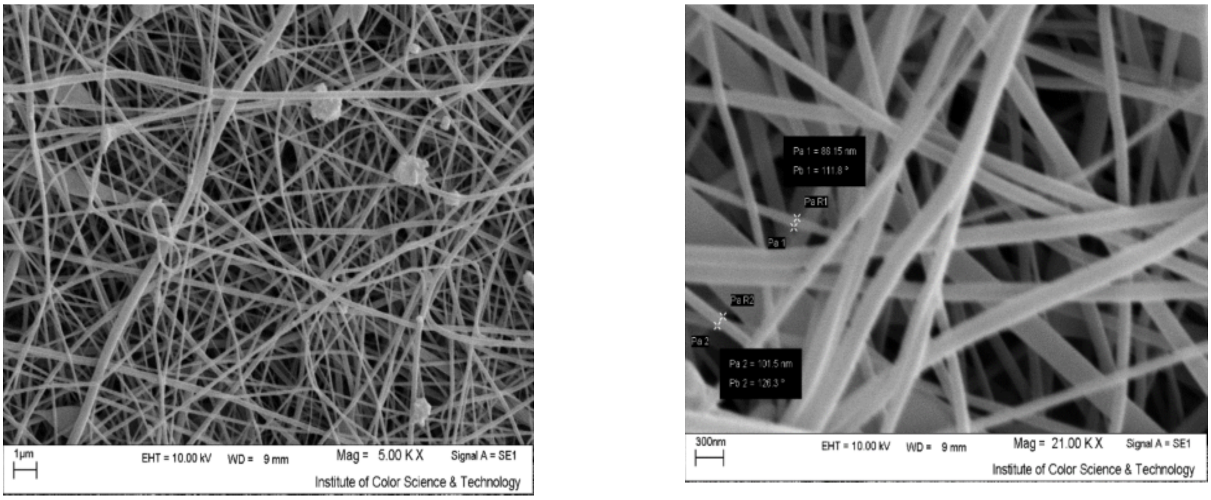
Fig. 15. FTIR of a) PAN25%w/w EDA nanofiber, b) P25E3%w/w Tectomer nanofiber, c) P25E5%w/w Tectomer nanofiber, d) P25E7%w/w Tectomer nanofiber, and e) P25E9%w/w Tectomer nanofiber (Almasian et al., 2015)



(a)



(b)



(c) (d)

Fig. 16. SEM images (a, d) PVA-chitosan and (b , c) PVA-chitosan crosslinks of mixed nanofibers (Mahmoodi and Mokhtari-Shourijeh, 2015)

The peak at 1059 cm^{-1} is attributed to acetal due to the reaction of glutaraldehyde with hydroxyl groups of PVA. Fig. 14 showed the FTIR spectrum of untreated PAN (polyacrylonitrile) and various PAN-EDA (polyacrylonitrile-ethylene diamine) nanofibers (Almasian et al., 2015).

In addition, Fig. 15 showed the FTIR spectra of PAN-25%w/w EDA and various Tectomer surface grafted PAN-25% EDA (P25Ex%Tectomer, x=3, 5, 7, and 9%, hereafter) nanofiber mats (Almasian et al., 2015). The SEM image shows that surface of the composite nanofibers in Fig. 16 has no signs of cracks and fracture, and the results show that a higher conversion rate reduces the adhesion between the nanofibers and the surface (Mahmoodi et al., 2019; Yang et al., 2013; Zuo et al., 2013; Yeul and Rayalu, 2013).

7. Conclusion

Various studies are being conducted to find a process to remove the dye that can be recycled and reused. Existing dye removal processes can be divided into three categories including biological, chemical, and physical methods. Colored wastewater contains several contaminants such as biologically active materials, dyes, soluble salts, etc. Several materials are used as adsorbents to remove dye from aqueous media. Among these nanomaterials, electrospun polymeric nanofibers have gained considerable attention from many researchers not only in the field of water treatment but also in other fields in the last two decades. More than 100 natural and synthetic polymers can be converted into electrospun polymeric nanofibers by dissolving them in suitable solvents and spinning them. Polymeric nanofibers have unique properties such as high surface area, high surface-to-volume ratio, and porosity.

In addition, there are adsorption sites and high adsorption capacity. These properties allow it to be used as an effective adsorbent for various pollutants such as dyes and other contaminants. The adsorption capacity of nanofibers increases with a reduction in pH. Considering the functional groups, there is an electrostatic attraction between the positively charged nanofiber and the anionic dye molecules. Increasing the pH causes reductions in the number of positively charged sites on the nanofibers. The decrease in dye adsorption with increasing contact time is attributed to the accumulation of dye molecules on the surface of the adsorbent, and the repulsive forces between the dye molecules on the adsorbent. The removal of dyes increases to a certain extent with the increment of the adsorbent dose, and after that, it reaches a certain amount, which increases the surface of the adsorbent and the availability of adsorption sites. With the increase of nanofiber dose, the number of active sites (NH_2) on the surface of nanofibers increases. The removal of dye decreases with the increase of the dye concentration, and if the amount of adsorbent is constant, the initial concentration of the dye on the adsorbent increases. Polymeric nanofibers obtained from the adsorption electrospinning process have been introduced as environmentally friendly and effective adsorbents for removing water contaminants. The treated dye wastewater is reused in the dyeing process and is not discharged into the environment to conquer the water shortage.

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