

Sustainable Wastewater Treatment Methods for Textile Industry



Aravin Prince Periyasamy, Sunil Kumar Ramamoorthy,
Samson Rwawiire and Yan Zhao

Abstract All over the world, environmental considerations are now becoming vital factors during the selection of consumer goods which include textiles. According to the World Bank, 20% of water pollution globally is caused by textile processing, which means that these industries produce vast amounts of wastewater. Generally, these effluents contain high levels of suspended solids (SS), phosphates, dyes, salts, organo-pesticides, non-biodegradable organics, and heavy metals. Increase in water scarcity and environmental regulations has led to textile industries to seek for sustainable wastewater treatment methods which help to reduce their water footprint as well as reduce their operational costs. Therefore, sustainable wastewater treatment could be the best choice for the textile industries with respect to the current issues. So, it is important to discuss and champion awareness mechanisms which help to reduce the current issues with respect to the textile wastewater. Therefore, this chapter intends to discuss the various sustainable wastewater treatments, namely granular activated carbon (GAC), electrocoagulation (EC), ultrasonic treatment, an advanced oxidation process (AOP), ozonation, membrane biological reactor (MBR), and sequencing batch reactor (SBR).

Keywords Wastewater · Effluent · Textile industry · Electrocoagulation
Water pollution · Pollution · Membrane bioreactor · Ultrafiltration
Activated carbon and sustainability

A. P. Periyasamy (✉)

Department of Materials Engineering, Technical University of Liberec, Liberec,
Czech Republic
e-mail: aravinprince@gmail.com

S. K. Ramamoorthy

Department of Mechanical Engineering, University of Borås, Borås, Sweden

S. Rwawiire

Department of Textile and Ginning Engineering, Busitema University, Tororo, Uganda

Y. Zhao

College of Textile and Clothing Engineering, Soochow University, Suzhou,
People's Republic of China

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1 Introduction

Among all planets in the solar system, the earth is notably a unique planet because of the life-supporting conditions present. Life forms of various nature, from microorganisms to human beings, dwell on earth. The environment that supports life and sustains various human activities is generally known as the biosphere. The term “environment” means surroundings. It is defined as “the sum of all social, economic, biological, physical, or chemical factors which constitute the surroundings of man whose task is to govern the environment.” The biosphere is a shallow layer compared to the total size of earth and extends to about 20 km from the bottom of the ocean, the highest point in the atmosphere at which life can survive, without man-made protective devices. Man’s habitation of the earth and his activities such as agricultural and industrial revolutions followed by the current high-tech world of synthetic and man-made materials have had a negative impact on the environment and biodiversity. Some the major impacts of man on the environment are discussed briefly below. Reduced child mortalities and developments in medicines had increased the lifespan of humans. The birthrate/m is 2–3 times higher than the death rates; with these rates, by 2050, the world’s population is expected to be around 9.8 billion compared to the current level of 7.6 billion [1]. This population stress leads to increase land habitation and demands, on resources like water, minerals, fossil fuels, and food, etc., all at the cost of major environmental degradation. Ongoing depletion of ground and surface waters, natural wealth, fossil fuels, forests, greenery and species diversity, due to overconsumption habits of human, is a permanent threat posed by humanity and the environment. There is rapid increase in deforestation which eventually leads to soil erosion, loss of plants and niche to other species, global warming and climatic changes. Deforestation, hunting, urbanization, and agricultural land reformation lead to the extinction and deprive the habitat to a vast variety of species, leading to endangered species and animals. However each and every biotic element has a role in nature’s harmony, the ongoing loss of biodiversity is a threat to natural ecosystems. The massive urbanization brings in the need for housing, utilities, buildings, industries, roads, transportation, infrastructures, water, and energy supplies. All this is attained at the cost of deforestation and loss of greenery. The end results are congestion, water, energy demands, pollution issues, and loss of biodiversity. Overconsumption of water for domestic, agricultural, and industrial needs ends in contamination of water sources, surface and groundwater depletion, and degradation. Water, a major abiotic element for support of life, is rendered useless for consumption by way of organic, mineral, toxic, bacterial, and physical pollutions. Water pollution is an alteration of physical, chemical, and biological properties of water in a water body, rendering it unsuitable for consumption. Water pollution renders it unsafe for human or animal consumption, for industry, aquaculture and agriculture or recreation leading to land, thermal, and marine pollution. The need for energy for domestic, transport, and industrial operations has, for instance, led to combustion of fossil fuels in due process delivering pollutant greenhouse gases like carbon

monoxide, carbon dioxide, nitrogen, sulfur, and carbon particles and add to the air temperature. Industrial emissions and chlorinated products also add potential contaminants into the atmosphere, the end results being acid rains, global warming, air toxicity, climatic change, and depletion of ozone layer. Deforestation and urbanization are the major causes of land abuse and soil erosion in due course leading to loss of fertility, contamination of pollutants—solid and liquid wastes on to land. The industrial revolution led to the birth of various industries, among them the textile industry. Textile industries have two divisions:

- Dry process—mostly engineering and assembling departments, which do not use water for all practical purpose (e.g., blowroom, carding, weaving).
- Wet process—departments which use water as raw material or in their processes or for both (e.g., chemical processing like coloration, printing, garment washing).

A couple of countries has the largest share of their gross domestic product (GDP) coming from textile and apparel industries; however, a hasty and unplanned clustered growth of these industries in most cases has environmental concerns. This chapter aims to present environmental challenges in textile industries and importance of sustainable wastewater treatment. Furthermore, it includes the comprehensive discussion of various conventional effluent treatments as well as its pros and cons as compared to various sustainable wastewater treatments, namely granular activated carbon (GAC), electrocoagulation (EC), ultrasonic treatment, advanced oxidation process (AOP) such as ozonation, membrane biological reactor (MBR), sequencing batch reactor (SBR), and rotating biological contactor (RBC). This chapter merely attempts to discuss the various sustainable wastewater treatments in textile industry, namely GAC, EC, ultrasonic treatment, AOP, ozonation, MBR, and SBR. This treatment could be a best choice for the textile industries with respect to the current environmental issues. Generally, the conventional wastewater treatments not only increase the landfill and extensive infrastructure needs, but also it changes the ecosystem when the landfill is not properly managed. In addition, these technologies consume considerable energy, which consequently emit the carbon emission. However, sustainable wastewater treatments provide significantly increased pollutant removal efficiency, and considerably reduce the sludge management, energy consumption, and running cost. In this process sequence, biologically based treatments offer high organic removal efficiency and adverse impact on the ecosystem, and also it ensures the sustainable sludge management which consume less energy; therefore, it reduces the overall cost.

2 Water Pollution Associated with Textile Industries

The coloration of textile involves a group of dyes, namely acid, direct, reactive, metal: complex, vat, sulfur, disperse and pigment. Generally, colorants are complex of organic or inorganic chemicals, and it can be applied to textile with different



Fig. 1 Textile effluent contaminates of Noyyal River at Tirupur, India

methods; however, the dye exhaustion is varied from 50 to 85%; therefore, dyes will discharge in the effluent as a pollutant, which badly affects the nearby water streams (Fig. 1). The color of dye wastewater changes the color of entire pollutant; however, it looks brownish red, black, or a mixture of both, and it also contains 4000–5000 parts per million (ppm) of SS [2–5]. Apart from a colorant, huge quantity of chemicals and auxiliaries are used during wet processing; in addition to process water, large volumes of cooling water are discharged as waste [6–10]. Apart from these effluents, solid wastes and liquid wastes as effluent are also discharged on land or into sewers or into natural water resources. The various effluents which are generated from textile chemical processing are given in Table 1, and the domestic standards for effluent discharge are given in Table 2. The effluent discharge standards for Indian textile industry are given in Table 3.

2.1 Effluent Discharged Various Operation of Textile Process

Melt and dry spinning operations produce not much effluent as compared to wet spinning [13]; however, wet spinning, for example, of viscose rayon produces huge pollutant in the wastewaters [14]. Table 4 shows the possible pollutant which caused by wet spinning and dry spinning. The basic steps involved in viscose rayon manufacture are wood pulping, soda cellulose formation and molecular fragmentation, solubilization with carbon disulfide, blending, wet spinning, washing, and finishing [15].

Table 1 Various pollutions caused by textile industry

Acids	pH reduction causes corrosion, help in the liberation of Na ₂ S, increase TDS, destroy microorganism, destroys self-purification system of water
Alkalis	Increase the pH, helps in the liberation of hydrogen ions, increase TDS, destroy microorganisms, destroy self-purification of water
Dissolved solids	Chlorides, sulfates, nitrates, bicarbonates of various inorganic metals, plants could be affected by osmotic changes, affect biological organisms, increase the COD and BOD
Suspended matter	Insoluble wastes, destroys self-purification of the stream of water, reduces the photosynthetic activity of plants, chokes the gill of fish, leads to floating masses, offensive odor
Dyes	Change the color of water, increase the COD and BOD, lead to cancer, disabilities, and disorders
Oils	Absorption of O ₂ from air into water affected, destroys the animal, plant life in water, increases the COD and BOD
Synthetic detergents	Reduce biodegradability, toxicity, accelerate chain reactions, increases floating masses, and affect natural aeration
Toxic metals	Self-purification of streams destroyed, cause skin diseases, disabilities, and disorders, destroy microorganism aquatic plants and animals are killed, compounds containing mercury affect the food chain
Pesticides	Fatal to fish, metabolic activities of body and photosynthesis of plants are affected
Gaseous pollutants	Include ammonia, free chlorine, hydrogen sulfide Increase toxicity, add on to oxygen demand, kill microorganism, destroy animals and plant kingdom
Heated effluents	Reduce dissolved oxygen concentration, aquatic life gets affected, destroy animal and plant kingdom, affect the entire ecosystem because of temperature
Radioactive wastes	All effects are numerous, induce metabolic changes, disorders, disabilities, genetic damage, chronic diseases, cancer, the abnormal birth of human beings which are also common to plants and animals

Table 2 Domestic effluent discharge standards [11]

Parameter	Inland surface water	Public sewers	Inland for irrigation	Marine coastal areas
pH	5.5–9.0	5.5–9.0	5.5–9.0	5.5–9.0
TSS (mg/l)	100.0	600.0	200.0	100.0
TDS (mg/l)	2100	–	2100	–
BOD (mg/l)	30.0	350.0	100.0	100.0
COD (mg/l)	250.0	–	–	250.0
Sulfates (mg/l)	1000.0	1000.0	1000.0	–
Chlorides (mg/l)	1000.0	1000.0	600.0	–
Oils and grease mg/l	10.0	20.0	10.0	20.0
Lead (pb) (mg/l)	0.1	1.0	–	2.0

Table 3 Limits to discharge for textile chemical processing in India (adapted from [12])

Parameters	Concentration not to exceed, milligram per liter (mg/L), except pH
Chemical oxygen demand (COD)	250
Biological oxygen demand (BOD)	30
pH	6–9
Total suspended solids (TSS)	100
NH ₃	15
Sulfide (S)	1
Total residual chlorine	1
Total chromium as Cr	2
Aniline	1
Oil and grease	10
Phenolic compounds as C ₆ H ₅ OH	1

Table 4 Effluent discharged by man-made fiber industries

Origin	Characteristics
Wood pulping	Alkali + surfactant (high TDS, BOD, COD)
Xanthation, dissolving	Carbon disulfide, alkali solution (high COD, alkalinity)
Spinning	Carbon disulfide, sulfuric acid zinc sulfate, sodium sulfate (high acidity, TDS, turbidity), solvents used in dry spinning
Washing and finishing	Sodium sulfide, sodium hypochlorite, hemicellulose (TDS, high BOD, COD)

As discussed earlier, chemical/wet processing of textile industry alone contributes 70% of the pollution. It is well known that textile wet processing consumes large amount of water for a various processes like sizing, desizing, scouring, bleaching, dyeing, printing, finishing, and other treatments (Fig. 2); further still, the different chemicals utilized lead to an acidic pH (Tables 5 and 6), and eventually, a large quantity of wastewater is discharged as a pollutant, which enormously spoils the water streams (Table 7).

Manufacturing of dyes and pigments deals with aromatic hydrocarbons amines, mineral acids like sulfuric and nitric acids and also involves a chain of reactions like starting toxic raw materials, intermediate steps like diazotization, coupling, sulfonation, nitration, etc.

The effluent from the dye industry is of high organic content, colored, and of high COD/BOD values. The dye and pigment industrial wastewaters are composed of insoluble organic pigments, dyes, heavy metals, emulsifiers which are shown in Table 8.

Fig. 2 Percentage share of water consumption in chemical processing of cotton materials

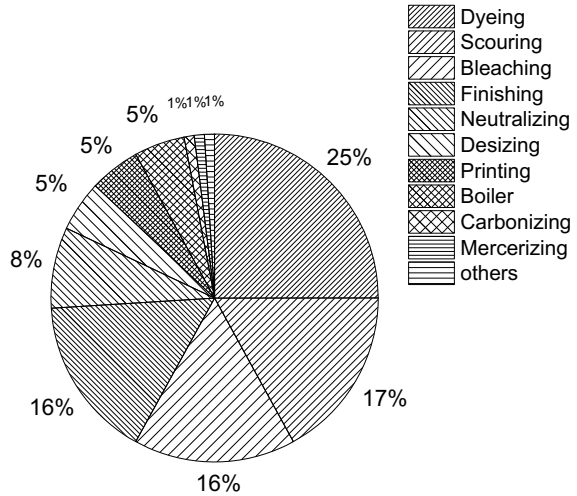


Table 5 General process parameters to be determined in pre-treatments

Parameters	Sizing	Desizing	Scouring	Mercerizing	Chlorite bleaching	H ₂ O ₂ bleaching
pH	7–9.5	7.3	10–13	14	6	10.5
TDS (mg/l)	–	8700–10,200	6323	12,000–5000	22,000	2400
SS (mg/l)	240–260	200–270	55	2200	6500	420
BOD (mg/l)	600–2500	4400–5060	2100	45–65	100	75
Color	Cream	Colorless	Brown	White	White	White
Odor	Bad odor	Bad odor	–	–	Bad odor	–

Table 6 General process parameters to be determined at coloration and combined effluent

Parameters	Dyeing	Printing	Combined effluent
pH	5–12.5	4–9	8–9.5
TDS (mg/l)	35,000	2000	20,000
Sus. solids (mg/l)	26,000	15,000–20,000	10,000
Total solids	40,000	2500	30,000
BOD/COD (mg/l)	300/1500	400/2000	250/400
Temperature °C	40–50	50	35
Heavy metals (mg/l)	450	400	420
Total alkalinity (ppm)	1600	–	–
Oils and greases (mg/l)	1900	–	3.6
Color	Heavily colored	Heavily colored	Heavily colored

Table 7 Effluent discharged by textile chemical processing

Origin	Characteristics
Sizing	Starch, colored, high BOD, suspended solids, PVA, odor, softener, oils fats [16]
Desizing	Starch, CMC, PVA, hydrolyzed starch, enzymes, salt, acidic pH [16–18]
Scouring	Alkalis, surfactants, saponified oils, hydrolyzed pectins, proteins, suspended solids, oil, high pH, silicates with high COD, natural colors, and TDS
Mercerizing	High alkali, suspended solids, TDS
Bleaching	Chlorines, hypochlorites, alkali, peroxides, silicates, suspended solids, fatty alcohol [16]
Dyeing	Dyes, salt, alkalis, acids, detergents, chromium, copper, high BOD and COD, and TDS [20–23]
Printing	Dyes, alkali, acids, chromium, copper, thickeners polymers, detergents high BOD and COD, waxes, oils fatty alcohol
Finishing	Silicons, suspended and dissolved solids, cationic compounds organic and inorganic compounds
Carbonizing	Carbonized cellulose, high acidity, TDS
Synthetics	Hot color, high BOD & COD, alkali, organic solvents, acidity, TDS, peroxides, hydrolyzed PVA, acrylics, etc.
Weight reduction	High alkalinity, turbidity, high BOD/COD
Wool scouring	Hot, highly colored, high BOD and COD, suspended and dissolved solids, grease, soaps, and alkalis
Silk degumming	Dissolved solids, high BOD, high turbidity, bad odor, TDS

Table 8 Effluent discharged by dyed and pigment manufacturing industries

Origin	Characteristics
<i>Dyes</i>	
Diazotization coupling reaction, nitration, sulfonation, halogenations, oxidation, reduction, and condensation reactions	Highly colored, high organic content, high BOD (200–400 mg/L), high COD (500–2000 mg/L), high BOD/COD ratio (0.2–0.4), acidic pH, high TDS, the presence of heavy metals like chromium, copper, cobalt, etc.
<i>Pigment</i>	
Grinding ball mills, washings	Highly colored, BOD, COD, turbidity of organic character [22]

3 Effluent Treatment Process

Wastewater from the textile industry is the main source of the organic contamination, which causes hemorrhage, ulceration of skin, nausea, skin irritation, and dermatitis. The contamination present in the effluent can block the sunlight and increase the BOD, therefore preventing photosynthesis and reoxygenation process. Various processes need to be implemented so as to reduce the pollution load; in this

case, many physical methods (adsorption, filtration methods, coagulation, and flocculation processes), chemical methods (oxidation, advanced oxidation, Fenton’s reagent), and biological treatment (anaerobic, aerobic) are carried out. The whole effluent process involves three steps (Fig. 3), namely primary treatment, secondary treatment, and tertiary treatment. In general, the primary treatments involve removal of the SS, floating and gritty materials, the secondary treatment involves reduction

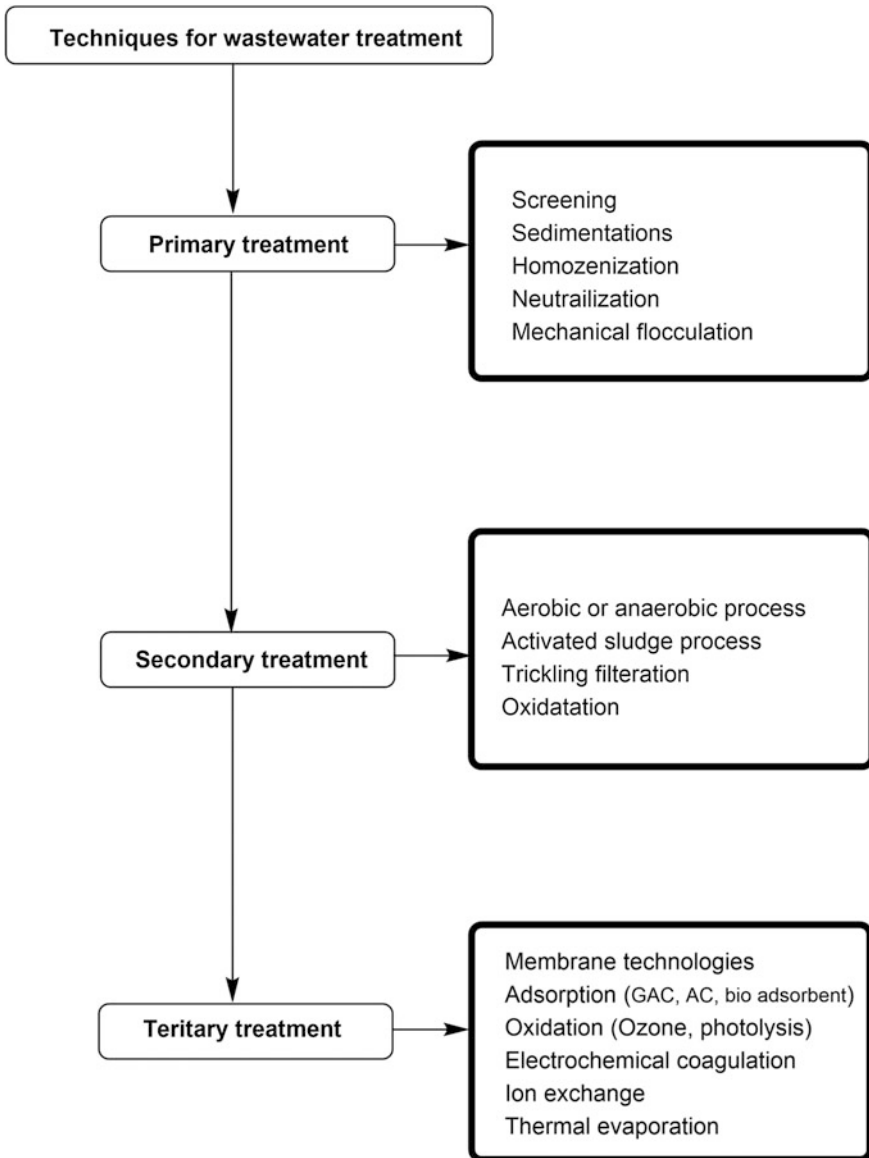


Fig. 3 Wastewater techniques for textile wet processing industries

of oxygen demands, other chemicals, and color of pollutant, and lastly, the tertiary treatment involves the removal of the final contaminates left over in the pollutant. After the treatments, treated water must be analyzed for the quality so as to gauge its reuse or discharge into the water streams [23–25].

Sustainable Wastewater Treatment and Overview of Existing Color Removal Methods

As discussed earlier, water and land is vital but is a limited resource, and it should not be polluted as a result of the industrial process. Therefore, the main task for the emerging technologies is to protect the earth from the pollution of industrial processes. In the present scenario, the conventional effluent treatment discharges huge quantities of sludge, which is an unwanted residue; perhaps sludge management is critical with respect to the environmental issues [23, 24, 26–28]. Sludge eventually ends up in landfills; however, it is not a safe practice since it leads to the pollution of air, water, and soil, also generates the uncontrolled landfill gases like methane, CO₂, and volatile organic carbons which proceed to global warming. During the landfilling, there is a huge possibility to contaminate the local groundwater due to the leaching potential [29]. Groundwater contamination from sludge is also an environmental concern and, therefore, quest for an alternative technology that can reduce the sludge during the effluent treatment is a step in the positive direction. In this case, chemical coagulation and other conventional effluent treatment process contribute significant impact on the sludge formation; therefore, it is advised to replace by electrocoagulation (EC) process. The colored water from textile effluent could be the biggest threat to the environment, and there are 12 classes of chromogenic groups, but azo and anthraquinone types are mostly used in the textile industry; both classes contribute 80% of total dye contributing to the textile colorants. On average, the dye house effluent contains 0.6–0.8 g dye l⁻¹ [30], hence the color and dye removal in the effluent becomes more important and it is a major scientific interest. In order to remove the colors from textile wastewater, various methods are used, such as chemical oxidation, coagulation and flocculation, membrane separation, aerobic and anaerobic degradation.

As there are some limitations such as the excess amount of chemical usage, accumulation of concentrated sludge that has serious disposal problems and lack of effective color reduction in some of these techniques, it has been shown to be effective. Based on the transfer of pollutants from the solution to the solid phase, it is known as the adsorption technique which is one of the efficient and general wastewater treatment methods. In terms of the initial cost, the simplicity of design, ease of operation, and non-toxicity of the utilized adsorbents, the adsorption method is superior to other dye removal techniques such as conventional wastewater treatment methods [31]. In selecting the adsorbent to remove organic compounds from wastewaters [31, 32], the main criteria are the cost-effectiveness, availability, and adsorptive properties and especially non-toxic and green adsorbent-based application of adsorption procedure with high surface area, and the reactive surface atom is a great demand [33, 34]. The existing process and alternative process are given in Table 9.

Table 9 Existing and alternative methods for textile effluent treatments

Existing methods	Alternative methods
Emulsion breaking	Multimedia filtration
Gravity-assisted separation	Carbon adsorption
Skimming	Ion-exchange
Plate/tube separation	Air-stripping
Dissolved air flotation	Activated sludge
Chromium reduction	Biological film or trickling filters
Cyanide destruction	Membrane bioreactors
Chemical precipitation	Electrodialysis (EC)
Filtration	Ultrafiltration
Sand filtration	Reverse osmosis

3.1 Primary Treatments

The purpose of primary treatment is to remove insoluble, invisible, and colloidal organic color and SS, and this treatment involves screening, equalization, neutralization, and coagulation followed by sedimentation steps. Primary reductions of COD and BOD value are also enhanced by this treatment. Various steps of primary treatment are as follows:

Screening

This process can remove the floating and suspended materials, and screens of various sizes and shapes are used depending on the nature of solids to be removed. Generally, fixed bar screens are the most used. Other simple screening equipment is mix mesh frames, alternate perforated plate frames, or damper plate with specific spacing. The screenings are disposed of by various methods such as grid, incineration, grinding, and digestion.

Equalization

The textile effluent has the difference in characteristics like color, turbidity, pH, BOD, COD, TDS, etc. Prior to the primary treatment, it is necessary to proportionately mix various process water to get together to achieve a uniform character. Equalization helps in providing such uniform effluent and prevents shock loads and sudden increase or decrease in pH due to some textile processes like mercerizing, scouring, carbonizing effluents entering the plant suddenly. Also, this process improves the dissolved oxygen (DO) levels.

Neutralization

Most of the secondary biological treatments are effective only if the pH value of effluent is between 6 and 9. However, extreme pH conditions make ineffective secondary treatments, since digestive bacteria can survive close to neutral pH conditions and are dead at extreme pH. Therefore, it is necessary to adjust the pH in the range of 6–9. Depending on the situations, dosing at regular uniform rate should

be done from the stored tanks containing the above liquors. Sometimes it becomes necessary to add dilute H_2SO_4 or CO_2 as per need.

Coagulation sedimentation

Coagulation sedimentation is one of the most used methods, especially in the conventional effluent treatment process. However, the action on the suspended matter, the colloidal type of very small size, and their electrical charge give repulsion and prevent their aggregation. In this case, add the electrolytic products (aluminum sulfates, ferric sulfates, ferric chloride) which can eliminate the surface electrical charge of the colloids. As per the environmental concerns, electrocoagulation can replace this process since it is not environmentally friendly.

3.2 Secondary Treatment Process

Presence of soluble organics, toxic metals, and organics may increase the BOD/COD values of effluent. The aim of secondary treatment is digestion of soluble organics by bacteria (aerobic or anaerobic mode), which improves the DO content, therefore resulting in reduced BOD/COD levels (80–85%) and toxicity. So, this process is enhanced by proper pH control (close to neutral), feeding of nutrients, prolonged interaction with air/oxygen, etc.

Aerobic

Aerobic biological treatment (oxidation) is carried out in the presence of air (open condition), so the soluble organics get converted into CO_2 and it could be removed out of effluent. Anaerobic biological treatment (treatment) is carried out under closed conditions in the absence of air; here, organic materials get converted into CH_4 or ammonia and are released out of effluent.

Activated sludge process

In this method, effluents were continuously exposed and subjected to biological degradation carried out by “microbial floc” suspended in the reaction tank, where the oxygen is introduced mechanical manner. The flocks formed in activated sludge process (ASP) are “zoology masses of living organism” embedded with food and slime material and are active centers of biological oxidation and therefore the name activated sludge process. A number of bacteria to be added depend on the organic matter present in the effluent to be treated.

3.3 Tertiary Treatment

The purpose of tertiary treatment is to remove dissolved solids (minerals, salts) from wastewater. The wastewater after efficient tertiary treatment can be safely

discharged or reused for processing. The modern effluent treatment plants employ the following tertiary treatment operations to separate dissolved solids and recover pure/safe water for reuse.

3.3.1 Membrane Technology

The membrane is a thin section of a material which arranged in suitable configuration (sheet or roll form); generally, it acts as a phase separator which permeable to one or like components [35]. Membranes are usually made up of polymers like as cellulose acetate/cellulose, triacetate polyamide, polyester, polypropylene, etc. The pore size of the membrane is usually expressed in micrometer/nanometers [36]. There are different membrane systems that could be used in textile wastewater treatment; they are micro-, ultra-, nano-, and RO filtrations, and each one has different cleaning properties (Table 10).

Microfiltration

Microfiltration process is based on the membrane technology; it can remove the particles in the range of 0.1–0.2 μm . The principle of microfiltration is a physical separation. Substances that are larger than the pores in the membranes are fully removed, meanwhile substances with smaller than the pores of the membrane are partially removed [38, 39]. However, SS, bacteria, pigments, oils, and large particles are removed. Microfiltration rejects ranges up to 10%. Microfiltration membranes are made of several polymers including poly (ether sulfone). Poly(vinylidene fluoride) and poly (sulfone). Ceramic, carbon, and sintered metal membranes have been employed where extreme chemical resistance or high-temperature operation can be carried out [21, 40].

Ultrafiltration

Ultrafiltration utilizes membranes to remove usually in the range of 500–1000 molecular weight. Ultrafiltration is generally preceded by conventional filters or cartridge filters to prevent blinding of the membranes. Periodically, the membranes must be cleaned by backflush technique. Ultrafiltration is used to separate polymers from salts and low molecular weight materials, with pores of 0.001 m–0.1 μm .

Table 10 Filtration spectrum of different membranes [37]

Process	Pore size (μm)	Molecular weight	Could be remove
Microfiltration	0.007–2.00	>100,000	Bacteria, pigments, oil, etc.
Ultrafiltration	0.002–0.10	1000–200,000	Colloids, virus, protein, etc.
Nanofiltration	0.001–0.07	180–15,000	Dyes, pesticides, divalent ions, etc.
Reverse osmosis	<0.001	<200	Salts and ions

Turbidity is sharply reduced by 99%. Polymers are retained for reduced Total Oxygen Demand (TOD), BOD, and COD. It is an excellent filtration technique to remove metal hydroxides and heavy metal up to 1 ppm or even less [21, 36, 39].

Nanofiltration

Nanofiltration membrane works similar to reverse osmosis (RO) except for pressure (less pressure is required for nanofiltration, i.e., 70 and 140 psi); it is due to the larger membrane pore size (0.05–0.005 μm). Nanofiltration removes the dyes, pesticides, and divalent ions, and also it is capable of removing hardness elements such as calcium or magnesium together with bacteria, viruses, and color. However, it operated with lower pressure than RO; therefore, operating cost is less than RO process [21, 36, 38–40].

Reverse Osmosis

In RO process, the good water is separated from pollutant through a membrane with the help of osmotic pressure. However, the RO process may be reversed by applying a pressure on the brine side higher than the osmotic pressure. A series of tubes made up of porous material is lined on the inside with an extremely thin film of cellulose acetate semipermeable membrane. These tubes are arranged in a parallel array; brackish water is pumped continuously with high pressure (>25 atm) through these tubes, and due to the high pressure, only water can penetrate through membrane and salt and another pollutant cannot, since the size of the pore can allow only water. Concentrated brine (reject) and freshwater (permeate) are withdrawn through their respective outlets. Prior to RO filtration, wastewater should be treated with sand filtration, activated carbon (AC) filtration, microfiltration, ultrafiltration, and removals of iron/calcium are necessary for smooth functioning. Generally, RO rejects ranges from 40 to 50% which is further run into the second stage and third stage of RO to recover maximum freshwater [41, 42].

Activated carbon treatment

AC is composed of a microporous, homogenous structure with high surface area (one gram of it has a surface area of approximately 500 m^2) and shows radiation stability which is widely used adsorbent in industrial processes. In the developing countries, the process for producing high-efficiency AC is not completely examined; moreover, there are several problems with the regeneration of used AC. Nowadays, there is a large curiosity in order to find inexpensive and effective alternatives to the existing commercial AC. When an effective and low-cost AC is explored effectively, it may contribute to environmental sustainability and offer benefits for future commercial applications. Comparatively, the costs of AC prepared from biomaterials are very low to that of the cost of commercial AC [43–46]. There are numerous studies which can be carried out to produce AC from waste

materials, such as waste wood [47], bagasse [48], coir pith [49], coffee husk [50], pinecone [51], coconut shell [52], and coconut flowers [53]. AC is ordinarily used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment. Both the physical and chemical process of accumulating a substance at the interface between liquid and solids phases is the adsorption. Due to the highly porous material and in providing a large surface area to which contaminants may adsorb, AC is an effective adsorbent. The two important types of AC utilized in water treatment applications are granular activated carbon (GAC) and powdered activated carbon (PAC). AC has the immense surface area and highly porous nature which allows the adsorbed compounds to penetrate the material fully, endeavoring out all available binding points. Chemical reactions also take place to change some offensive compounds into less objectionable variations. Even though the AC is not effective against all compounds, it does have the ability to bond with compounds in all three phases: liquid, solid, and gas.

Production

A wide variety of carbon-rich precursor materials such as bituminous coal, anthracite, sub-bituminous coal, lignite, wood, coconut shells, and peat are used to produce ACs. By either thermal or chemical activation processes, these materials are converted into AC. Steam gasification (activation) and chemical activation used reactive, inorganic additives at relatively lower temperatures and are typically included in thermal treatment. Bituminous coal can be classified as direct-activated or re-agglomerated to produce the ACs. Direct activation is involved to size the coal approximately to the required particle size and thermally activating the sized coal. Comparatively, direct activation can produce a less costly product to that of re-agglomeration. Re-agglomeration involves first pulverizing and briquetting the coal with organic binders. The desired particle size is achieved through the stage crushing the briquettes. The binder is also converted to a graphitic structure that interconnects the activated coal particles when the agglomerated material has been activated. Both the hardness and abrasion characteristics of re-agglomerated and direct-activated GAC are frequently comparable. In order to have a better certain organic contaminant removal, re-agglomerated carbons tend to have a more homogenous pore structure. All the carbonaceous raw material reacts during thermal treatment by means of condensation reactions to form increasingly larger aromatic plate structures. The characteristics of the raw materials influence the density of the structure. In order to have more extensive structures, the raw materials must be denser such as bituminous coal. Within the GAC particle, these outstretched flat graphite platelets are placed indiscriminately to provide the extensive internal structure needed for adsorption to occur. AC treatment effectively removes chlorine-phenols chlorinated hydrocarbons, surfactants' color, and odor-producing substances from textile effluent. It can also substantially reduce harmful contaminants including heavy metals such as copper, lead, mercury, disinfection by-products. AC filters are positively charged that attract and trap many contaminants and prevent them from passing through the pores in AC filters can

become plugged over time making them ineffective to remove any more contaminants. Thermal regeneration is generally used to reactivate the carbon by which the organics are evaporated out. In series when one is exhausted can be removed from service or column can be replaced. In parallel columns, both the beds become saturated simultaneously and both have to be replaced. AC can be added directly to the effluent, which eliminates needs of carbon adsorption beds. DuPont developed a process in which powdered AC is directly added to the aeration tanks [54–56].

Granular activated carbon

Granular activated carbon (GAC) is a particular formulation of AC, or activated charcoal. In ancient India, for drinking water filtration AC was used, and as a multi-use purifier in ancient Egypt. In modern day, in the early nineteenth century, it was introduced to Europe's sugar refining industry. Organic materials with high carbon contents such as wood, lignite, and coal are used in making GAC. The essential feature that distinguishes GAC to PAC is its particle size. Depending on the material used and manufacturing process, GAC typically has a diameter ranging between 1.2 and 1.6 mm and an apparent density ranging between 25 and 31 lb/ft³. The bed density is about 10% less than the apparent density and is used to determine the amount of GAC required to fill a given size filter. To promote stratification after backwashing and minimize desorption and premature breakthrough, the uniformity coefficient of GAC is quite large, typically about 1.9, which results in mixing AC particles and adsorbed compounds with AC particles. A process is known as adsorption work through the preparations of AC. In absorption, like as a sponge soaking up water compounds are evenly distributed throughout the absorbent product. In creating a film, however in adsorption, the compounds bind only to the surface molecules and carbon molecules are naturally attractive. Therefore, they actively seek to bond to other molecules [57, 58].

Working

For locating a GAC treatment, there are two most common option units in water treatment plants, such as:

- a. Post-filtration-adsorption—after the conventional filtration process (post-filter contactors or adsorbers), the GAC unit is located,
- b. Filtration-adsorption—GAC replaces some or all of the filter media in a granular media filter.

Examples of these configurations are shown in Figs. 4 and 5, respectively. The GAC contactor receives the highest quality water in post-filtration applications, and thus, it has the only objective to remove the dissolved organic compounds. Adsorbers which are backwashed are usually unnecessary unless excessive biological growth occurs. By providing longer contact times than filter-adsorbers ensure the stipulates of most flexibility for handling GAC and for designing specific adsorption conditions.

The filter-adsorber configuration uses the GAC for turbidity and solid removal from textile effluent, and biological stabilization in addition to dissolved organics

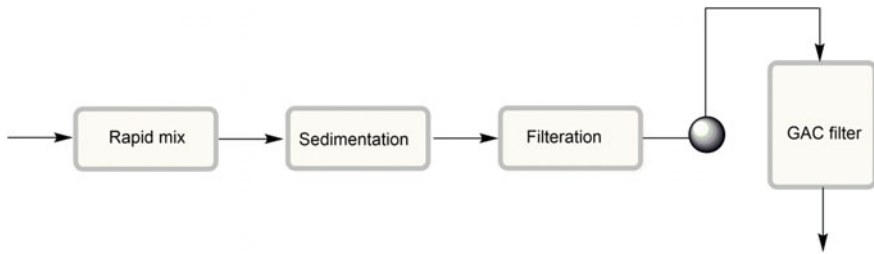


Fig. 4 Post-filtration-adsorption of granular activated carbon process

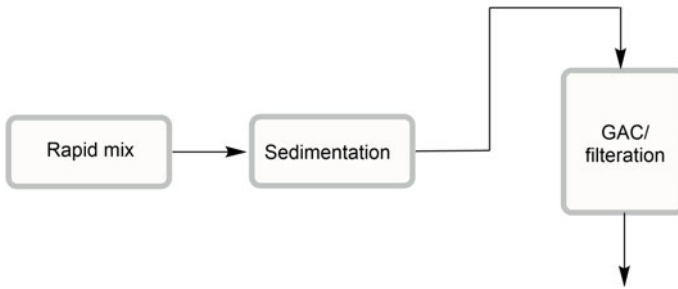


Fig. 5 Filtration adsorption of granular activated carbon process

removal. By replacing all or a portion of the granular media with GAC, the existing rapid sand filters can often be retrofitted for filtration-adsorption. Capital costs are reduced significantly by retrofitting existing high-rate granular media filters since no additional filter boxes, under-drains, and backwashing systems may be needed. Nevertheless, filter-adsorbers backwashed more frequently than post-filter-adsorbers (filter-adsorber units are backwashed about as frequently as conventional high-rate granular filters) since it has shorter filter run times and in addition, due to increased backwashing filter-adsorbers may incur greater carbon losses and may cost more to operate because carbon usage is less effective. In order to determine the required GAC contactor volume, the primary factors are the (i) breakthrough, (ii) empty bed contact time (EBCT), and (iii) design flow rate. The time when the concentration of a contaminant in the effluent of the GAC unit exceeds the treatment requirement is the breakthrough time. The GAC is exhausted and must be replaced/regenerated when the GAC effluent concentration is greater than the performance standard for over three consecutive days which is considered as a rule of thumb. The EBCT is calculated as the ratio of empty bed volume to that of flow rate through the carbon. By increasing the bed volume or reducing the flow rate through the filter, the longer EBCTs can be achieved. The amount of carbon to be contained in the adsorption units is defined by the EBCT and the design flow rate. Breakthrough and reducing the GAC replacement/regeneration frequency can be delayed by longer EBCT. Formerly the optimum EBCT is established, the

carbon depth and adsorber volume can be determined. Typical EBCTs for water treatment applications range between 5 and 25 min. For GAC filters, the surface loading rate is the flow rate through a given area of GAC filter bed which is expressed in units of gpm/ft^2 . Surface loading rates for GAC filters typically range between 2 and 10 gpm/ft^2 . Highly adsorbable compounds which can be used in high surface loading rates are targeted for removal. The surface loading rate is not important when the mass transfer is controlled by the rate of adsorption as is the case for less-adsorbable compounds. The carbon usage rate (CUR) is used to determine the rate at which carbon will be consumed and how often carbon must be replaced/regenerated. By increasing, contact times improve with carbon treatment effectiveness. The percentage of carbon is increased by the deeper beds that are exhausted at breakthrough. After carefully evaluating the capital investment, the optimum bed depth and volume are typically selected and operating costs associated with reactivation frequency and contactor construction costs [59–63].

GAC contactors can be organized as either,

- Downflow fixed beds,
- Upflow fixed or expanded beds, or
- Pulsed beds, with single or multiple adsorbers operated in series or in parallel.

Each unit is connected in series with downflow fixed beds in series with the first adsorber in order to acquire the highest contaminant loading and the last unit receiving the lightest contaminant load. From the first unit, carbon is removed for reactivation, with the next adsorber becoming the lead unit. For parallel downflow fixed beds, each unit acquires the same flow and contaminant load. In order to maximize the carbon usage, multiple contactors are frequently operated in a parallel-staggered mode in which each contactor is at a different stage of carbon exhaustion. Since effluent from each contactor is integrated, individual contactors can be controlled beyond breakthrough such that the blended flow still meets the treatment goal. To remove the SS, periodic bed expansion is permitted by the up flow expanded beds and allows using smaller carbon particles without significantly increasing the head loss. Removal of spent carbon occurs from the bottom of the bed while fresh carbon is added at the top without system shutdown in the pulsed bed adsorbers. A pulsed bed cannot be entirely washed-out, which prevents contaminant breakthrough in the effluent [59–63].

3.3.2 Evaporation

Evaporation is an important tertiary treatment process; in textile industry, evaporation is used to dehydrate the concentrated solutions (e.g., caustic recovery from mercerizer) and separate dissolved solids, dyes, water from dye bath, and the rejected water from nanofiltration and RO process can be separated through evaporation through vaporizing and condensing of pure water. In case of effluent treatment, the permeate from RO as well as condensate water from evaporator

results in pure distilled/demineralized water which can reuse in various textile processing or boilers [64–66]. Textile effluent is usually evaporated by the following two options.

- a. Solar evaporation
- b. Mechanical evaporation

Solar evaporation

The saline effluent (concentrate dye bath, first wash, rejected from RO, nanofiltration) is let into the large surface area in the open tanks, called as solar ponds (0.5–0.75 m height). For continuous operation and retention, multiples of solar ponds are constructed which gets filled up on a daily basis. The wind flow and sunlight available during daytime evaporate the surface water, and vapors are taken into the atmosphere (Fig. 6). The dissolved solids or concentrated dehydrated mass gets settled at the bottom and is periodically removed. The sludge is usually taken for secured landfilling storage.

Advantages

- Simple construction
- No energy costs involved
- No maintenance required
- No skilled technicians are required



Fig. 6 Solar evaporation plant used in small-scale textile coloration units in Tirupur, India

Table 11 Operating conditions for typical multiple evaporation plant (adopted and modified from [37])

Parameter	Stage I	Stage II	Stage III	Stage IV
Temperature °C	82	72	62	55
Length of tube (meters)	6	6	4.5	4.5
Diameter of tube (meters)	90	90	45	45

Disadvantages

- Very slow rate of evaporation
- Ineffective during raining seasons, low wind flows, cold climate, etc.
- Calls for larger surface area
- Chances of overflow contamination into groundwater in case of rain
- The release of water vapor into atmosphere leads to lack of recovery of pure water back for recycling.

Mechanical evaporation

Mechanical evaporators are heated by steam condensing on metallic, cylindrical tubes. As steam condensates on the outside of the tube, the heat of condensation causes saline water slurry on the inside of the tubes of the cylinder to get boiled. A mechanical evaporation is a device used for desalination or separation of pure liquid from admixtures, dehydration of dilute solution for concentration, separation of pure water from effluent slurries. In textile effluent treatment, evaporators are used for direct evaporation or stagewise concentrating saline effluent called as multiple effect evaporation plant (MEEP) (dye bath, first wash, RO, or nanorejects) followed by fluid crystallizer to separate solid and water. Evaporators can be batch or continuous operation, and the configuration can be vertical or horizontal. MEEP is a vertical cell in which stainless steel tube could be mounted; however, some of the evaporators are working with falling liquid film theory. The tube is heated with through steam, in generally the concentrated liquid is collected in the bottom of the evaporator, which is sent to next stage of the evaporator, where the freshwater is added to the first stage of the evaporator. Meanwhile, steam could be applied to the first stage of the evaporator; the next stage of evaporator gets steam from previous one. During evaporation, the liquid is re-circulated till it gets desired concentration [67, 68]. The operating parameters for MEEP are given in Table 11,

3.3.3 Electrocoagulation (EC)

Electrocoagulation was first proposed by Vik et al. [69]. It was designed for London sewage treatment plant. In 1909, Harries J. T received the USA patent for wastewater treatment by electrolysis using sacrificial electrodes made through aluminum and iron. Later, Matteson et al. [70] described the “Electro Coagulator” which can produce aluminum hydroxide from hydroxyl ions by using aluminum

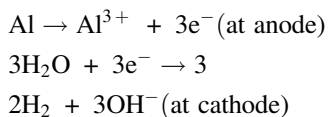
electrodes. Electrocoagulation (EC) is a well-established technology for the sustainable treatment of wastewater without the addition of chemicals such as Ferric, polyaluminum chloride (PAC). It is an electrochemical process which removes the SS, colloidal material, and metals, as well as other dissolved solids from the wastewater. Literally, the process called as “electrolysis” which breaks the substance by using of electricity; here direct current (DC) can be applied through to metal electrodes, and it starts reacting on an atomic level at the electrode–water interface from neutral, elemental state to charged state [71]. Thereafter, the charged metal atoms left the plate and enter into the water. Therefore, the electricity is applied to the electrodes to create the charged metal coagulant which bonds with dissolved contaminants, precipitates out of solution, organics adsorb to the precipitated solids, and solids agglomerate and separate, in another word electrical current destabilizes the SS allowing them to precipitate. Generally, the electrode is made from mild steel or aluminum which consume electrochemical reaction, therefore it should be replaced periodically [72]. The advantage of this process is that it generates less sludge than another conventional coagulation process such as a chemical method. Further, it is easy to dewatering the sludge, which drastically reduces the disposal cost. Also, it removes wide range of pollutant which includes heavy metals, suspended/colloidal solids, bacteria, BOD, COD, hydrocarbons, pesticides, and herbicides. Typical removal efficiency is around 95% and plus, and this process is good pre-treatment to membrane technologies where the high quality of water is required to reuse (Table 12). Presently, this process has gained attention due to its ability to treat large volume and for its low cost [73–76].

Table 12 Electrocoagulation treatment with a different type of dyes

Dye	Current or current density	Anode cathode	Removal efficiency (%)	References
Reactive orange 84	130 A/m ²	SS–SS, Fe–Fe	66, 76	Yuksel [77]
Reactive Black B, Orange 3R, Yellow GR	0.0625 A/cm ²	Al–Al	98	Khandegar [78]
Reactive Black 5	7.5 mA/cm ²	Fe–SS	90	Patel [79]
Remazol Red RB 133	15 mA/cm ²	Al–Al	92	Can OT [80]
Direct Red 23	30 A/m ²	Fe–Fe, Al–Al	>95	Phalakornkule [81]
Acid Red 14	80 A/m ²	Fe–St 304	93	Daneshvar [82]
Acid Orange 7	5 mA/cm ²	Boran-doped diamond–copper foil	98	Fernandes [83]
Disperse Red	20.8 mA/cm ²	Al–Al	95	Merzouk [84]

Mechanism of Electrolysis

In this process, coagulant can be generated due to the electrochemical reactions which produce the ions and help to remove the various kinds of pollutants either by chemical reaction and precipitation or by causing the colloidal materials to coalesce. The main processes occurring during the electrochemical reaction is electrolysis which held in the electrodes, formation of coagulants in the aqueous phase, adsorption of soluble or colloidal pollutants on coagulants, and removal by sedimentation and floatation. The main chemical reaction in the electrodes is as follows;



The flocculation and coagulation in the EC technique have the advantage that it can be possible to remove the small colloidal particles, whereas in the conventional method it could not be. In addition, it reduces the sludge levels and also it is a very simple process, therefore easy to operate. The simple principle of electrolysis is shown in Figs. 7 and 8.

Mode of EC operation

The mode of EC operation can be divided into two categories, which is batch and continuous processes. A continuous process of EC can be operated under steady-state conditions, particularly with respect to the fixed pollutant concentration and effluent flow rate; however, it is perfectly matched with bulk quantity (i.e., for industrial) of effluent, whereas batch reactors are suited to laboratory and pilot plant scale applications. In a continuous process, it is very easy to control the operational parameters; therefore, it provides the better efficiency. The batch process is mostly time-dependent, and the coagulant is continuously generated by the reactor with the dissolution of anode. Therefore, anode can hydrolyze the pollutants, so the concentration of pollutant, coagulant, and pH can change time to time. The schematic representation of batch and continuous EC processes is given in Fig. 9.

Impact of Various Operating Parameters

However, the efficiency of EC process can be depended on the various operational parameters such as conductivity of the solution, arrangement of electrode, electrode shape, type of power supply, pH of the solution, current density (CD), distance between the electrodes, agitation speed, electrolysis time, initial pollutant concentration, retention time, and passivation of the electrode [86].

Solution conductivity

In the electrolysis, solution conductivity is very important; however, removal efficiency and operational cost of EC process are based on the solution

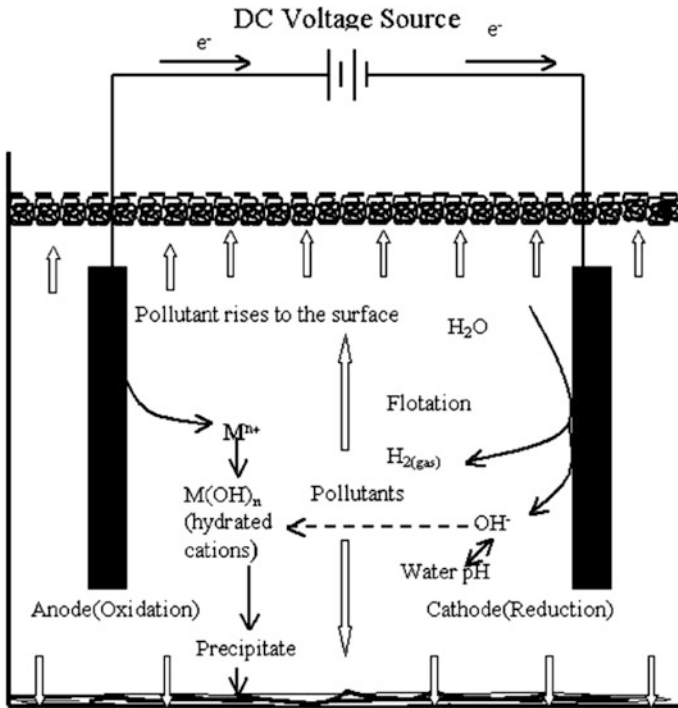


Fig. 7 Simple principles of electrocoagulation process (reprinted from [85], with kind permission of Elsevier publications)



Fig. 8 Laboratory-scale electrocoagulation process

conductivity. In general, the solution must have minimum conductivity, and then only electric current could be flowing in the solution. However, the addition of electrolyte (sodium chloride or sodium sulfate) can regulate the conductivity of low-conductivity wastewater. Perhaps, the energy consumption could be less in case of higher conductivity solution [87].

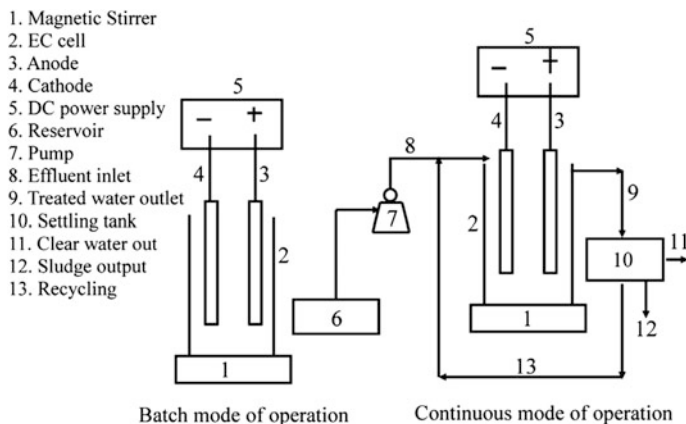


Fig. 9 Schematic diagram of batch and continuous modes of operation (reprinted from [86], with the kind permission of Elsevier publications)

Arrangement of electrodes

In EC process, the operational cost linearly depends on the connection mode of the electrode; however, it is confirmed by a previous study [88, 89]. Nasrullah et al. [89] studied the different arrangement of electrodes and their efficiency. Therefore, authors used to keep the electrodes in parallel, series, monopolar, and bipolar aluminum electrodes to find the optimum results. The arrangements (i.e., monopolar parallel (MP-P), monopolar series (MP-S), and bipolar (BP)) of the electrode can be described in the Fig. 10. The anode and cathodes are arranged in parallel order with respect to the MP-P setup; here the electric connection can be divided into the electrodes. In MP-S, electrodes are connected to the power source forming anode and cathode, while a pair of the inner electrodes (also called as sacrificial electrodes) is connected to each other without any connection to the power source. In BP configuration, there are two sacrificial electrodes which are placed in between the two parallel electrodes without any connection. Also, authors used different electrode orientation, namely vertical, horizontal orientation with anode at the bottom and horizontal orientation with anode on top; among these, vertical orientation provides higher percentage of COD removal, and it reached 59% with respect to the 120 m, whereas horizontal orientation with anode at the bottom shows only 40% of same time.

The results for the different arrangement of electrodes, MP-S showed 65, 65, and 60% for COD, BOD, and SS, respectively, in 120 m, whereas BP shows 56, 56, and 51%, which is lowest treatment efficiency toward to various pollution parameters (Fig. 11). It is clearly shown that the highest removal efficiency can get through serial connection than parallel connection. This is due to the higher consumption of anode material; therefore, the efficiency of pollutant treatment purely depends on the anodic dissolution in the system, where higher dissolution of anode makes more coagulants to the system, which assures more treatment efficiency.

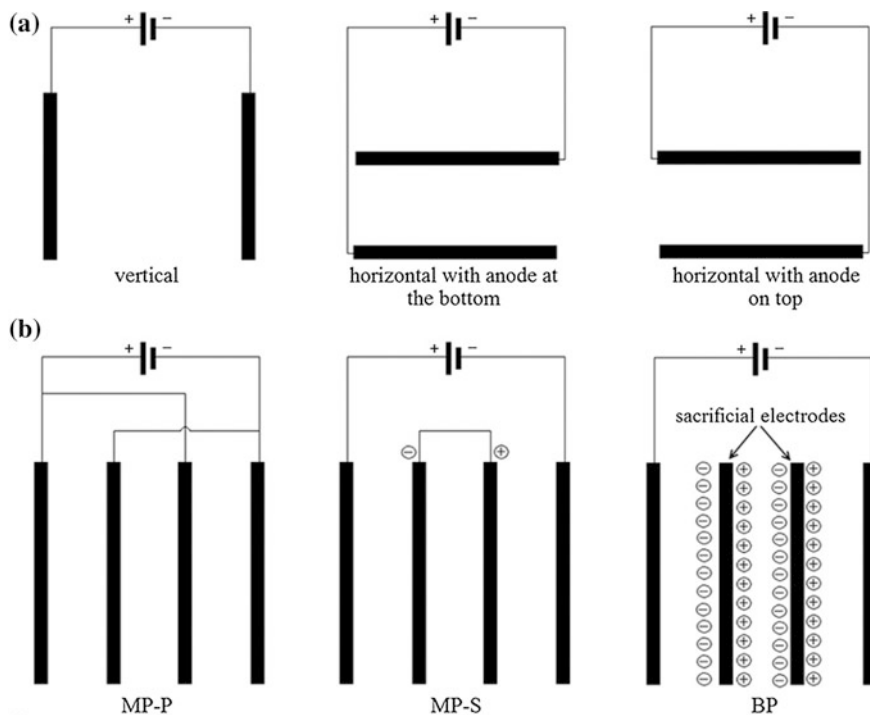


Fig. 10 Arrangement of electrode in EC process: **a** orientations, **b** arrangements (reprinted from [89], with the kind permission of Elsevier publications)

Rotating anode

Ahmed Samir et al. [90] studied the overall efficiency of novel rotating electrodes with respect to the various speed and different CD on textile effluent (Imperon Violet KB (CAS #: 6358-46-9) for the fabric dyeing process.), schematic representation of rotating electrode are shown in Fig. 12.

The overall results of total removal efficiency are shown in Fig. 13, COD removal efficiency is 90% when the anode was static with no rotational speed ($CD = 8 \text{ mA/cm}^2$) for the time period of 30 m, meanwhile the efficiency can be increased to 91% by increasing the rotational speed of electrode by 75 rpm and reduced the $CD = 4 \text{ mA/cm}^2$ for the time period of 10 m; similarly, the efficiency can be increased to 95% by increasing the rotational speed of 150 rpm with the same CD, and during this period, the formation of $\text{Al}(\text{OH})_3$ flocs which connected to other pollutants makes precipitation easier. But when the electrode speed is increased to 250 rpm, there is no COD removal efficiency can be achieved, which is due to the extremely high speed of the electrode cannot make the electrolysis process. In general, COD removal efficiency was increased by increasing the CD. The initial color and TSS were decreased within 10 m with the rotational speed of

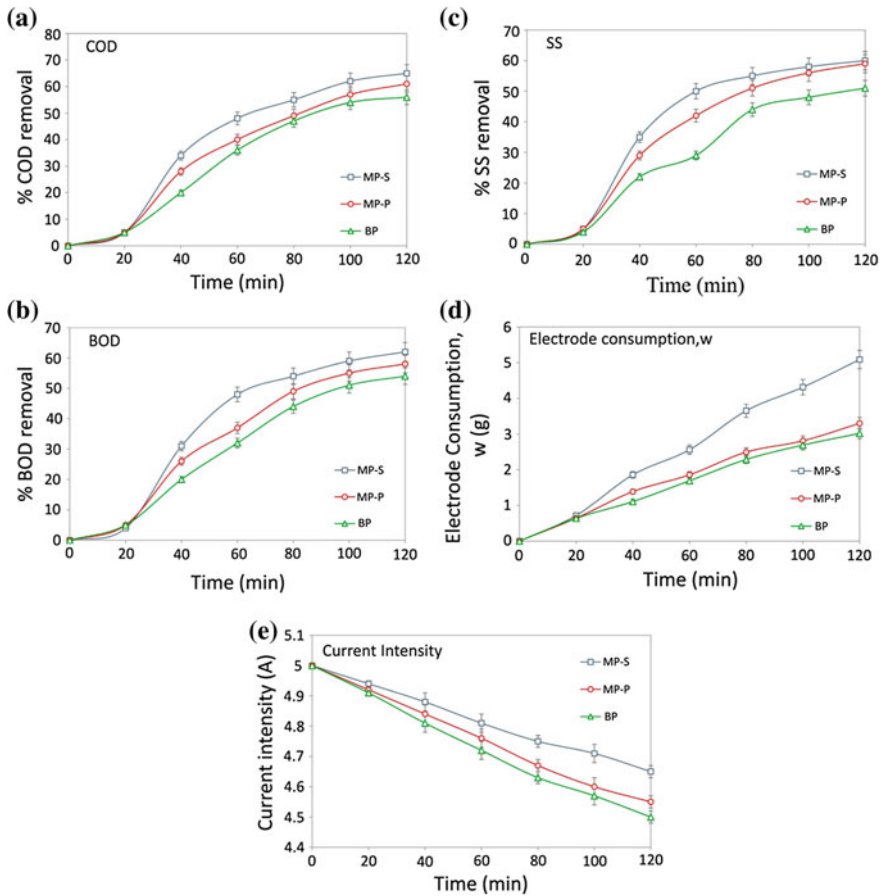


Fig. 11 Effect of MP-S, MP-P, BP as electrode arrangements on **a** COD removal, **b** BOD removal, **c** SS, **d** anodic dissolution, and **e** current intensity changes during 120 m (reprinted from [89], with the kind permission of Elsevier publications)

150 rpm, and the results were significantly varied with respect to the CD; however, very good color removal can be obtained by application of 8 mA/cm².

Shapes of the electrode

In EC process, the shape of electrodes is directly influenced on the pollutant removal efficiency. Yosuke Kuroda et al. [91] studied on the different shape of electrodes with respect to their pollutant removal efficiency and concluded that the punched hole type of electrode shows higher removal efficiency than the electrode without punched holes (Fig. 14). However, there are very few studies conducted on and reported in this field [92]. Kuroda et al. [91] reported in their studies the higher discharge current for the electrode with punched holes. However, the higher discharge current is directly influenced by higher pollutant removal efficiency. Perhaps, it still required higher number of studies to establish this study.

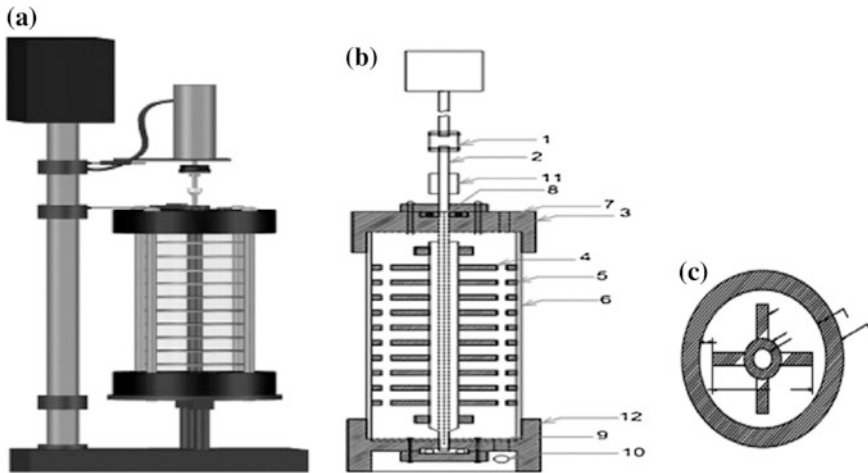


Fig. 12 **a** Schematic diagram of EC rotated anode system. **b** Details of EC rotated anode reactor: 1. motor variable speed; 2. stainless steel shaft; 3. upper Teflon flange cover; 4. Al rods of impellers anode; 5. Al rings of cathode; 6. Perspex reactor; 7. upper ports; 8. ball bearing; 9. thrust bearing; 10. lower port; 11. zoom coupling; 12. lower Teflon flange cover. **c** Top view of impellers anode with ring cathode (reprinted from [90], with kind permission of Elsevier publications)

Type of power supply

In the EC process, the electrolysis reaction can be performed through electrode, and it required electric voltage; the majority of the research has used DC and few are in alternative current [93, 94]. However, the use of DC leads to corrosion formation on the electrode due to the metal oxidation during the EC process, and also the oxidation layer can be formed in the cathode and followed by it reduce the current flow between the cathode and anode, results are reduced pollutant removal efficiency. Subramaniyan et al. [95] have studied the effect of alternative current and DC on pollutant removal efficiency of cadmium from water by using the aluminum alloy as anode and cathode. They obtained improved results with respect to the alternative current (97.5%) than DC (96.2%) (Fig. 15), at 0.2 A/dm² of CD with pH of 7, the results provide the information that alternative current will reduce the formation of corrosion in the electrode, which resulted in increased removal efficiency.

Eyvaz [94] analyzed the effects of alternating current electrocoagulation on textile wastewater for dye removal, and wastewater containing disperse yellow 241 (DY) and reactive yellow 135 (RY) dyes. They obtained the results of dye removal efficiency which are plotted in Fig. 16; in overall the reactive dye (RY) shows lower removal efficiency than disperse dye (DY) in both the power (i.e., alternative current and DC). However, after 100 m, alternating current power supply shows higher removal efficiency for both the dyes, which means that increasing the operation time can increase the accumulation of dye residue causing passivation on cathode material.

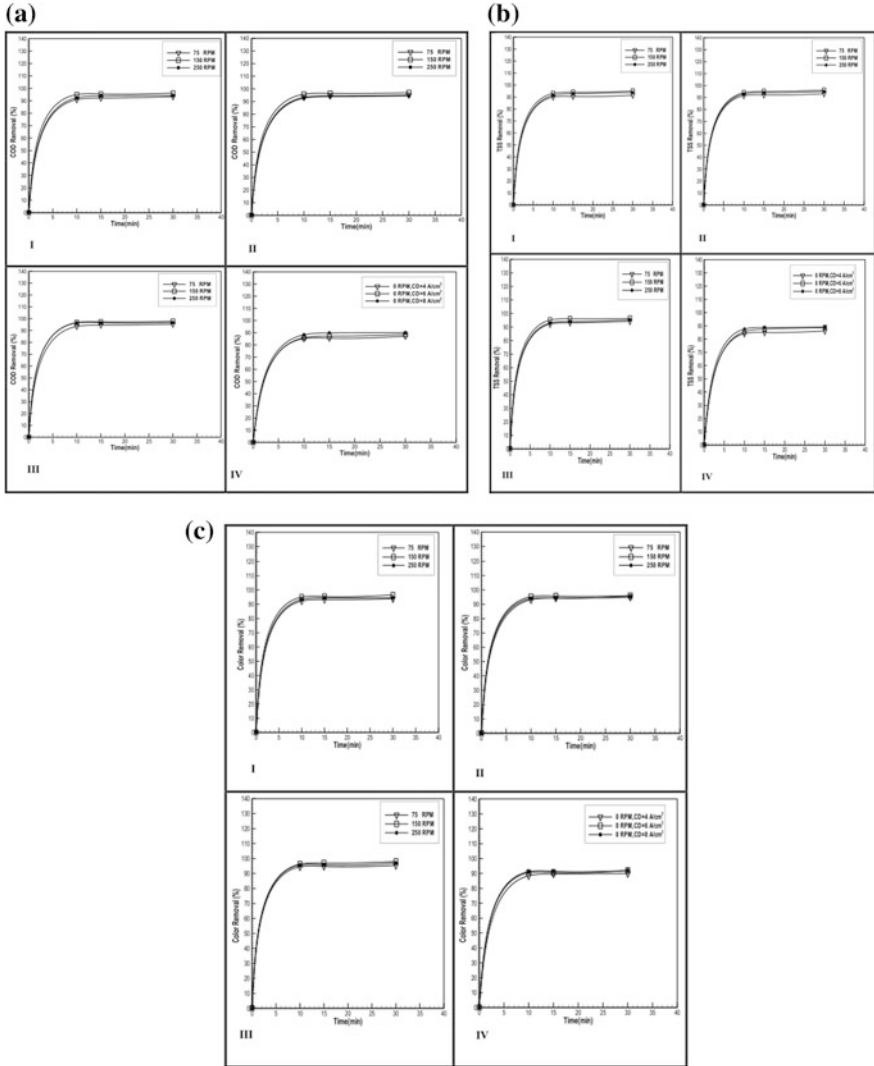


Fig. 13 a Effect of rotational speed on COD removal, I. CD = 4 mA/cm²; II. CD = 6 mA/cm²; III. CD = 8 mA/cm²; IV. Zero rotational speed. b Effect of rotational speed on TSS removal, I. CD = 4 mA/cm²; II. CD = 6 mA/cm²; III. CD = 8 mA/cm²; IV. Zero rotational speed. c Effect of rotational speed on color removal, I. CD = 4 mA/cm²; II. CD = 6 mA/cm²; III. CD = 8 mA/cm²; IV. Zero rotational speed (reprinted from [90], with the kind permission of Elsevier publications)

pH of the solution

In the process of electrocoagulation, the important operational parameter is the pH of the solution. For a particular pollutant, the efficiency of removing the maximum pollutant is obtained at an optimum solution pH. At a particular pH, the

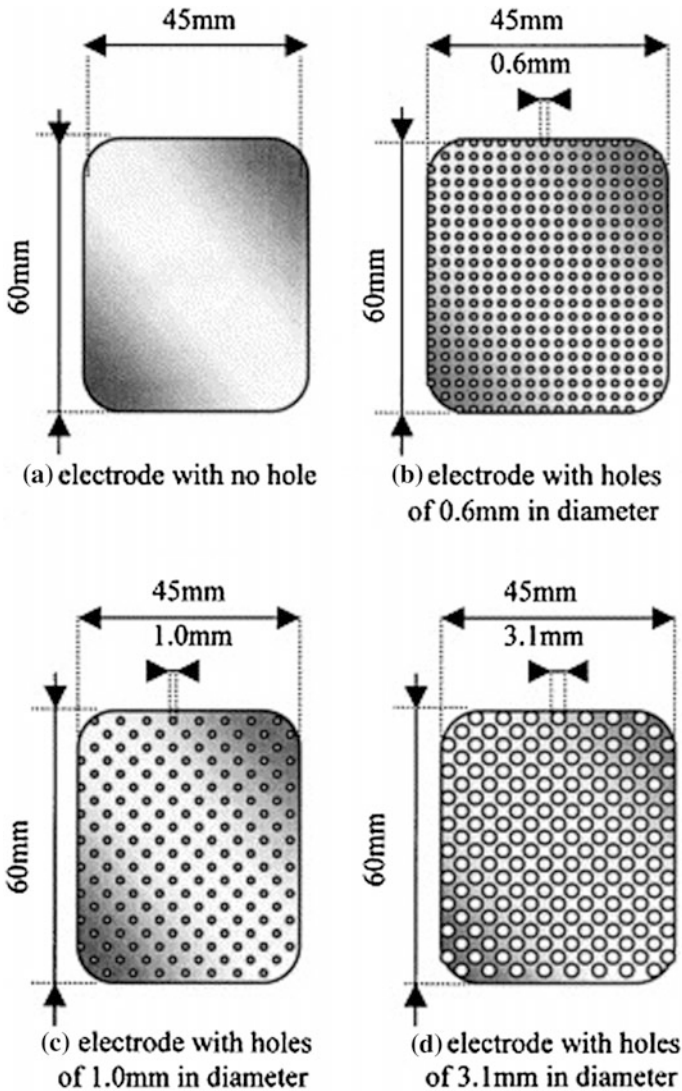


Fig. 14 Different electrode shapes used in EC process (reprinted from [91], with the kind permission of Elsevier publications)

precipitation of a pollutant begins. The pH of the solution from the optimum pH either decreases or increases according to the decreasing the pollutant removal efficiency. The removal of hexavalent chromium from synthetic solution was studied by Verma et al. [96] using electrocoagulation and found that the pH of the solution has a significant effect on the Cr(VI) removal efficiency. At different pH of the synthetic solution, they performed the experiments and acquired the maximum chromium removal efficiency at the pH 4. They concluded that the synthetic

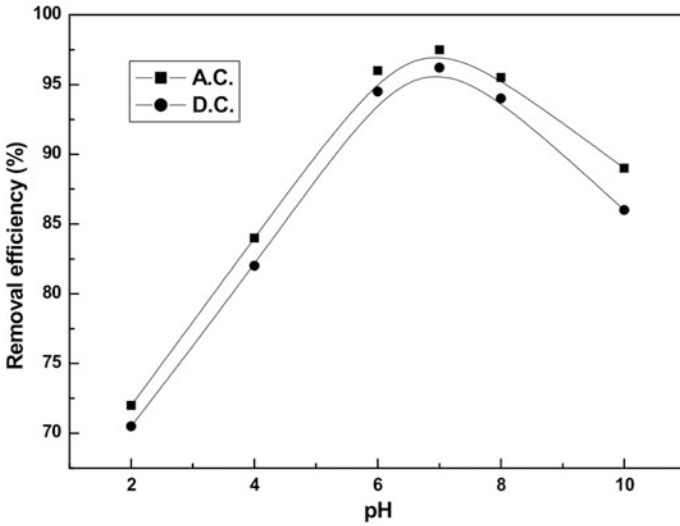


Fig. 15 Effect of pH of the electrolyte on the removal of cadmium. Conditions: an electrolyte concentration of 20 mg/l; a current density of 0.2 A/dm²; temperature of 303 K (reprinted from [95], with the kind permission of Elsevier publications)

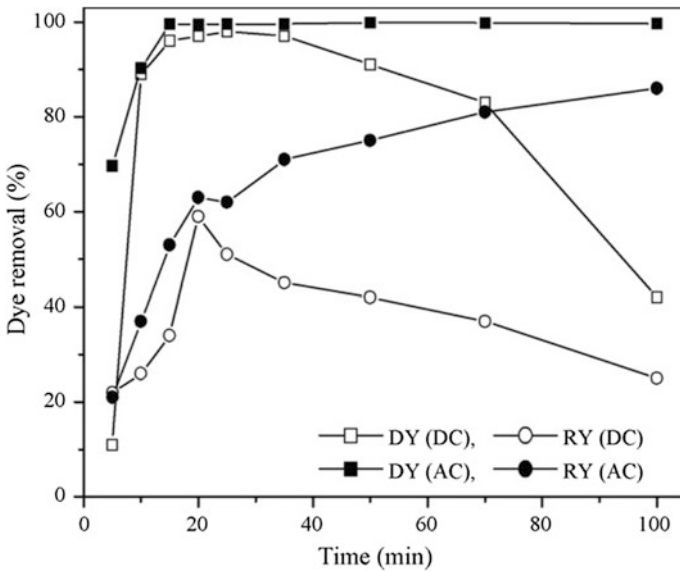


Fig. 16 Effects of power supply type on dye removal in view of operation time (reprinted from [94], with the kind permission of Elsevier publications)

solution pH increases after the EC process with an increase in the electrolysis time due to the generation of OH in the EC process.

Fajardo et al. [88] have studied the influence of initial pH, applied CD and initial dye concentration on the efficiency of EC process with respect to textile wastewater. To assess the pH influence, they used different pH (3, 6, and 9) by adjusting with H_2SO_4 or NaOH. The pollutant removal efficiency was calculated with respect to the time; there is a significant improvement in COD removal when the initial pH of pollutant at 3, meanwhile, pH 6 and 9 could not show much difference within 30 m, thereafter all pH shows almost similar results. However, after 120 m, pH 9 will give a better result than another pollutant. In the case of color removal, before 60 m, there is a huge difference in the efficiency and thereafter the results are almost nearer, which means there is no significant difference (Fig. 17).

Current density

In electrocoagulation, the important parameter, namely CD, determines the coagulant dosage rate, bubble production rate, size and growth of the flocs, and in turn, it affects the efficiency of the electrocoagulation. As the CD increases, the anode dissolution rate increases. As a result, it increases the number of metal hydroxide flocs resulting in the increase in pollutant removal efficiency. When the CD increases above the optimum CD, it does not result in an increase in the pollutant removal efficiency due to a sufficient number of metal hydroxide flocs are procurable for the sedimentation of the pollutant. Fajardo et al. [88] also studied the impact of applied CD (i.e., authors used 4 and 16 mA/cm^2) on the color removal; the results are plotted in Fig. 18. However, the highest color removal efficiency of 97.1% was found with respect to the 16 mA/cm^2 at the time period of 90 m. Conversely, 360 m was necessary to achieve similar decolorization percentage when 4 mA/cm^2 was applied. Apart from that, the COD removal efficiency is not showing the significant difference with respect to the applied CD.

Distance between the electrodes

The electrostatic field depends on the distance of anode and cathode; therefore, it plays a significant role in EC process. Maximum pollutant removal efficiency could be found with at optimum distance of anode and cathode. Perhaps, pollutant removal efficiency is less when the electrode distance is minimum; it is due to the metal hydroxides generated and followed by flocs, which refuse to sediment. Daneshvar et al. [82] studied the effect of interelectrode distance and their pollutant removal efficiency of Acid Red 14 dye. The result is shown in Fig. 19; color removal efficiency can be increased with increasing the distance of interelectrode (anode and cathode). This is due to the electrostatic effects between the interelectrode during the EC process; therefore, the distance increases, movement of produced ions could be slow in the action and possible to aggregate and produce the flocs.

Effect of agitation speed

In order to maintain uniform conditions, the agitation is helpful and it avoids the formation of the concentration gradient in the electrolysis cell. Further, for the

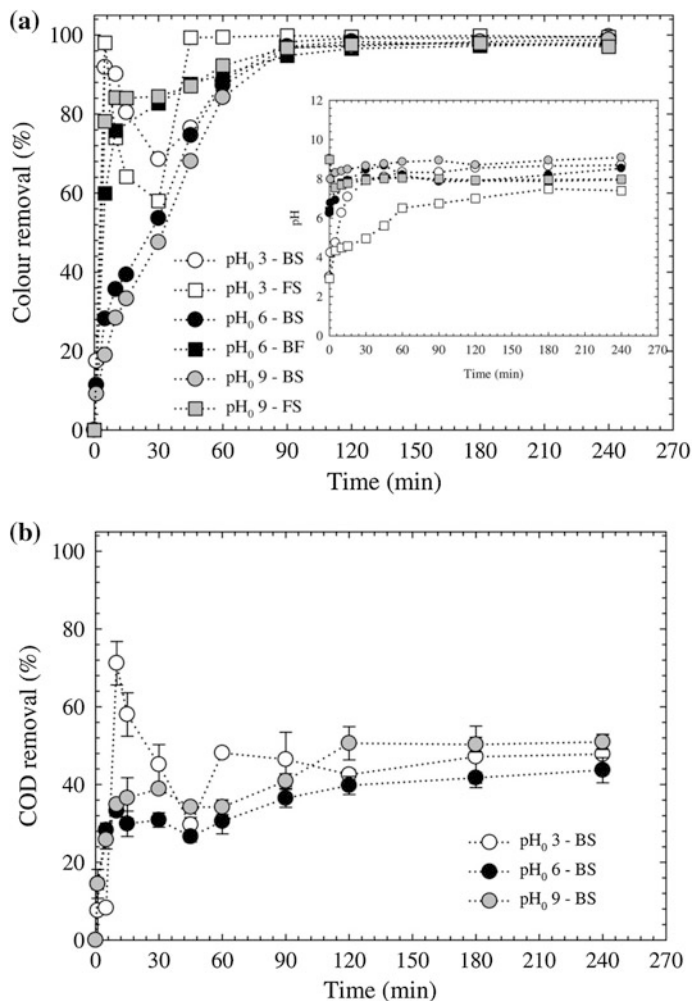


Fig. 17 Effect of the initial pH on color (a) and COD (b) removals over time. Inset a: pH evolution over time. Operating conditions: $j = 16 \text{ mA/cm}^2$, 100 mg/L of Reactive Black 5, stirring rate = 800 rpm (batch system), and flow rate = 160 l/h (flow system) batch-stirred system (BS) versus recirculation flow system (FS) (reprinted from [88], with the kind permission of Elsevier publications)

movement of the generated ions, the agitation in the electrolysis cell imparts velocity. In order to increase the pollutant removal efficiency, the agitation speed is increased up to the optimum agitation speed. For a particular electrolysis time, the flocs are formed much earlier which consequently increase the pollutant removal efficiency due to the fact that with an increase in the mobility of the generated ions. But there is a decrease in the pollutant removal efficiency when it is increased

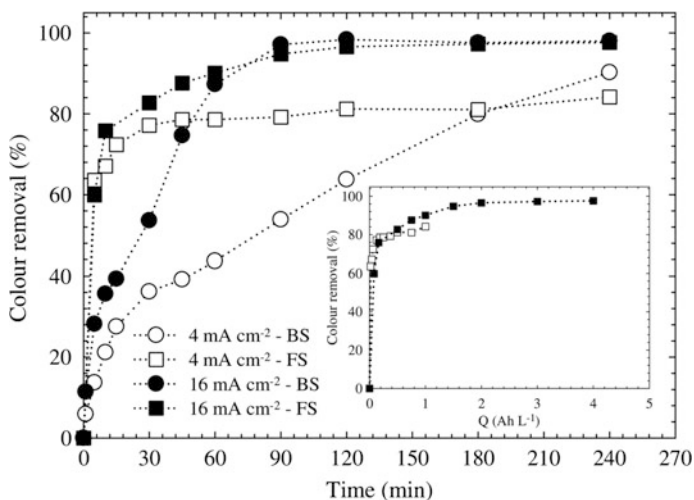


Fig. 18 Effect of the current density on color removal over time, for batch and flow systems. Inset: Color removal as a function of the applied charge at different current densities for the flow system. Operating conditions: pH = 6, 100 mg/L of Reactive Black 5, stirring rate = 800 rpm (batch system), and flow rate = 160 l/h (flow system) (reprinted from [88], with the kind permission of Elsevier publications)

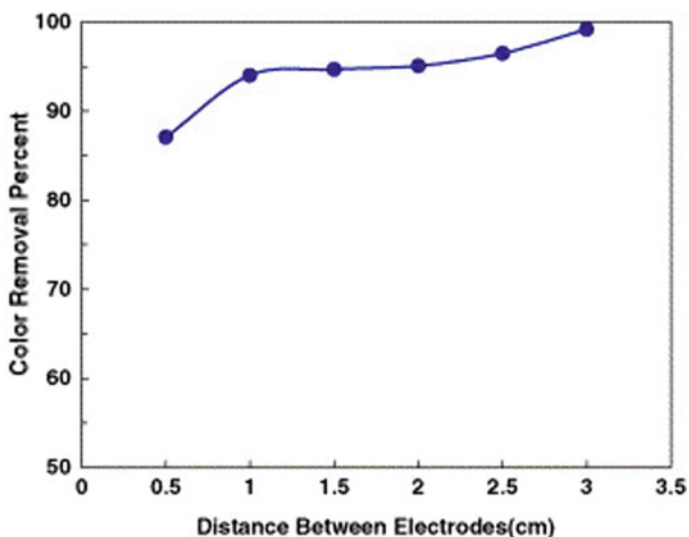


Fig. 19 Effect of interelectrode distance on the efficiency of color removal from a solution (reprinted from [82], with the kind permission of Elsevier publications)

further in the agitation speed beyond the optimum value, as the flocs get degraded by collision with each other due to high agitation speed [97].

Electrolysis time

One of the functions of electrolysis time is the pollutant removal efficiency. With an increase in the electrolysis time, the pollutant removal efficiency increases. But when it goes on the far side of the optimum electrolysis time, the pollutant removal efficiency remains constant and does not increase with an increase in the electrolysis time. By desolating the anode, the metal hydroxides are formed. When a CD is fixed, the number of generated metal hydroxide increases with an increase in the electrolysis time. There is an increase in the generation of flocs for a longer electrolysis time, resulting in an increase in the pollutant removal efficiency. When the electrolysis time goes beyond the optimum electrolysis time, the pollutant removal efficiency does not increase as sufficient numbers of flocs are available for the removal of the pollutant. Aoudj et al. [98] studied the different operational parameters of EC process for Direct Red 81 containing effluent. In this study, they studied the reaction time, results are plotted in Fig. 20, and the results are increased from 52.5 to 98.28% by increasing the time from 10 to 60 m, since other parameters are constant (CD of 2.5 mA/cm², initial dye concentration, 50 mg/L and initial pH 6). However, the reaction has linear relationship with pollutant removal efficiency of EC process. This is due to the anodic electrodisolution which led to release the coagulating process. In general, the dye removal efficiency depends on the concentration of metal ions which can be produced by electrodes. Therefore, the concentration of metal ions is directly proportional to the electrolysis time.

Initial concentration of pollutant

For a constant CD, there is an increase in the initial concentration of the pollutant as the pollutant removal efficiency decreases. Due to the insufficiency of the number of metal hydroxide flocs formed in order to sediment the greater number of pollutant molecules at higher initial pollutant concentrations [99]. Therefore, lower the initial

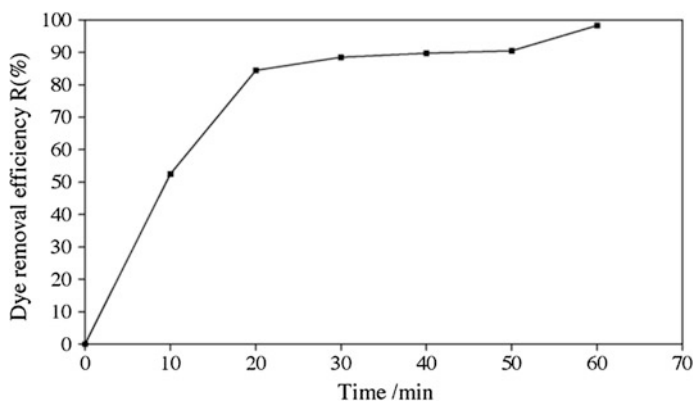


Fig. 20 Effect of time of electrolysis on the removal efficiency of Direct red 81 (reprinted from [98], with kind permission of Elsevier publications)

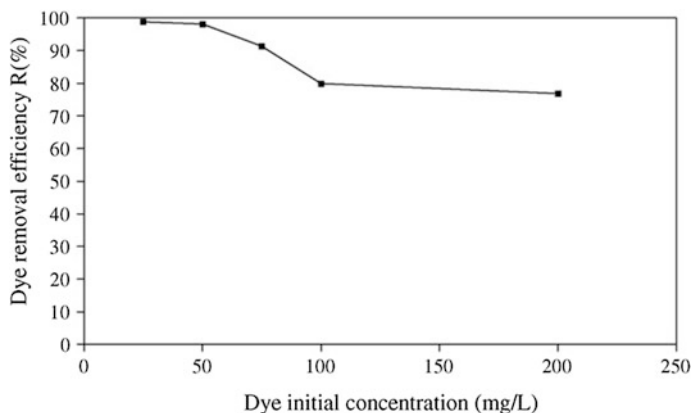


Fig. 21 Effect of initial dye concentration on the removal efficiency of Direct Red 81 (reprinted from [98], with the kind permission of Elsevier publications)

dye concentration makes better decolorization efficiency. Aoudj et al. [98] obtained the results of initial dye concentration with respect to dye removal efficiency, and when the initial dye concentration is increased from 25 to 200 mg/L, the dye removal efficiency could be decreased from 98 to 76% (Fig. 21).

Retention time

Once the electrocoagulation process for a particular electrolysis time is completed, the solution is kept for a fixed period (retention time) in order to allow settling of the coagulated species. The removal efficiency of pollutant increases as the retention time increases. Due to the increase in retention time, all coagulated species settle down easily to give clear supernatant liquid and the sludge. The optimum retention time resulting in the reduction of pollutant removal efficiency as the adsorbed pollutant desorbs back into the solution [82]

The advantages of electrocoagulation as compared to chemical coagulation are as follows:

- Compared to the chemical coagulation, EC requires no addition of chemicals and also provides better removal capabilities for the same species.
- As the chemical coagulation cannot remove many species but for EC removes.
- In order to lower the sludge disposal cost, EC produces less sludge.
- EC sludge can be utilized as a soil additive which is more readily filterable
- EC sludge contains metal oxides which makes it pass the leachability test.
- EC technique process can be started by turning on the switch which needs only a minimal startup time.

Some of the limitations of the electrochemical coagulation are as follows:

- Periodically, the sacrificial anodes need to be replaced.

- Depending on reactor design, the electrocoagulation requires a minimum solution conductivity in order to limit its use with effluent containing low dissolved solids.
- In case of the removal of organic compounds, there is a possibility of formation of toxic chlorinated organic compounds from effluent containing chlorides.
- On the cathode, an impermeable oxide film may be formed which may provide resistance to the flow of electric current. However, changing the polarity and cleaning of the electrodes periodically may reduce this interference.
- There is an increase in the operational cost of EC due to the high cost of electricity.

3.3.4 Advanced Oxidation Process (AOPS)

The main goal of AOP is to produce and use the hydroxyl free radical (HO), and it is a strong oxidant and destroys the compound; however, it is not possible by the conventional oxidant [100]. Generally, we use conventional oxidation process to treat the drinking water; nevertheless, this process may not destroy all kind of toxins. Every oxidizing agent has the different oxidation potentials, which are listed in Table 13. AOP is characterized to produce the OH radicals, and it can specifically attack, this is the biggest versatility, and also it can produce different methods which are given in Table 14.

Ozonation

Ozone is a strong reactive gas with oxidation properties; generally, it is unstable, explosive, and easily recognized by its smell. However, it is toxic in nature even very less concentration, the density of ozone is ~ 1.5 times higher than the atmospheric air [102–105]. Ozone has very good solubility in water than the oxygen. However, ozone can be used to treat the drinking water to kill the microorganisms like bacteria and other living things [106]. The mass transfer of ozone from gas-phase to liquid-phase is a limiting step. The driving force and

Table 13 Conventional oxidizing agents and its oxidizing potential

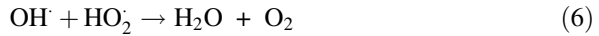
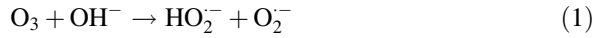
Oxidizing agent	EOP (V)	EOP related to chlorine
Fluorine	3.06	2.25
Hydroxyl radicals	2.8	2.05
Atomic oxygen	2.42	1.78
O ₃	2.08	1.52
H ₂ O ₂	1.78	1.3
Hypochlorite	1.49	1.1
Chlorine	1.36	1
Chlorine dioxide	1.27	0.93
Oxygen (molecular)	1.23	0.9

Note EOP Electrochemical oxidation potential

Table 14 Different methods to generate AOP with respect to the wastewater treatment (reprinted from [101], with the kind permission of Springer publications)

AOP types	Oxidant for advanced oxidation	Other occurring mechanisms
O ₃	OH [·]	Direct O ₃ oxidation
O ₃ /H ₂ O ₂	OH [·]	Direct O ₃ oxidation H ₂ O ₂ oxidation
O ₃ /UV	OH [·]	UV photolysis
UV/TiO ₂	OH [·]	UV photolysis
UV/H ₂ O ₂	OH [·]	UV photolysis H ₂ O ₂ oxidation
Fenton reaction	OH [·]	Iron coagulation Iron sludge-induced adsorption
Photo-Fenton reaction	OH [·]	Iron coagulation Iron sludge-induced adsorption
Ultrasonic irradiation	OH [·]	Acoustic cavitations generate transient high temperature
Heat/persulfate	SO ₄ ⁻	Persulfate oxidation
UV/persulfate	SO ₄ ⁻	Persulfate oxidation UV photolysis
Fe (II)/persulfate	SO ₄ ⁻	Persulfate oxidation Iron coagulation Iron sludge-induced adsorption
OH ⁻ /persulfate	SO ₄ ⁻ /OH [·]	Persulfate oxidation

efficiency of ozone treatment can be varied, and it is based on the nature of the liquid (i.e., concentration, pH of the effluent). A simple reliable method is used to inject ozone into the closed tank which contains the wastewater. The remaining ozone which is not consumed in the process would be destroyed in the off-gas with the help of thermal catalytic unit. There are two methods can produce the ozone, ultraviolet, and corona discharge. Generally, it is applied to wastewater through diffuser tubes or turbine mixers. The dosage of 2 mg/L itself shows significant impact on the pollutant removal efficiency [107, 108]. The previous literature shows that the degradation of azo dyes with ozone is quite limited; however, the ozone readily attacks the electron-rich molecules [105, 109, 110]. The oxidation potential of organic-inorganic matters by ozone is 2.07 V; however, in some cases, higher dose rate cannot help to convert organic matters to CO₂ and H₂O completely, particularly with textile dyes, which has the combination of effluent (surfactant, suspended matters, and other auxiliaries). Ozone treatment can produce the better pollutant removal efficiency when the parameters are optimized, such as temperature, pH, and applied ozone dose [111]. A simple decomposition mechanism of ozone in aqueous solution illustrated in the following equation [104],



Pazdzior et al. [112] studied the influence of ozone on textile effluents; therefore, they applied different ozone doses from 1.68 to and 0.14 g O₃ dm⁻³; a diagram for the laboratory ozone treatment is shown in Fig. 22.

Ozone doses were showing significant improvement in the toxic reduction of textile dye (C.I Reactive yellow 186), the highest concentration of ozone dose will reduce ~50% of total toxic units than the control sample (sample without ozone treatment), and the results are shown in Fig. 23.

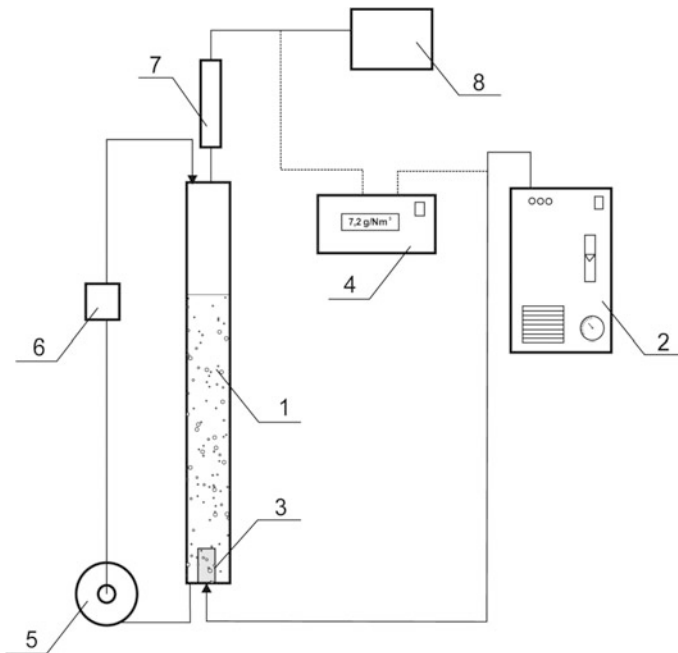


Fig. 22 Laboratory setup for ozonation process: 1 bubble column; 2 ozonator with oxygen concentrator; 3 gas diffuser; 4 gaseous ozone analyzer; 5 peristaltic pump; 6 cell for samples collecting; 7 scrubber filled with silica gel; 8 ozone destructor (reprinted from [112], with the kind permission of Elsevier publications)

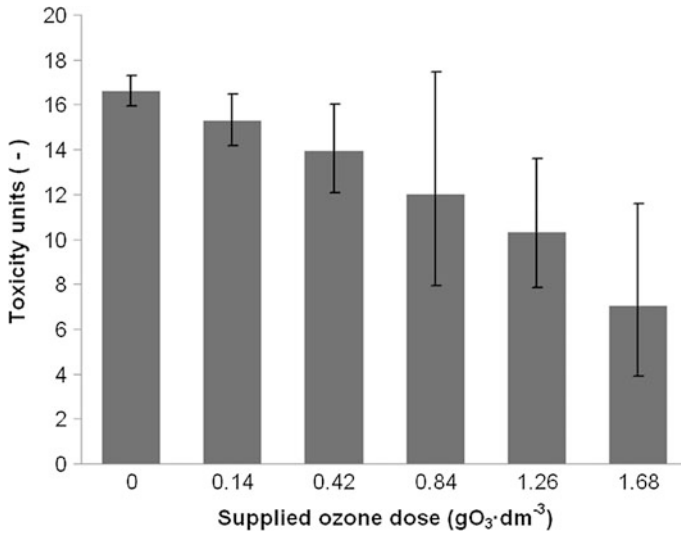
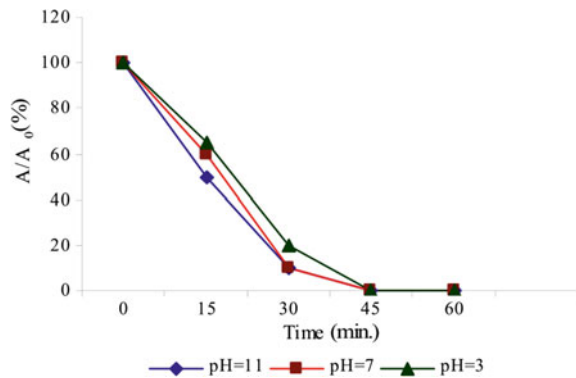


Fig. 23 Toxicity changes for different ozone doses (reprinted from [112], with the kind permission of Elsevier publications)

Fig. 24 Effect of pHs on percent UV absorption of Congo red at different ozonation time (reprinted from [113], with the kind permission of Springer publications)



During the ozone treatment, pH of the effluent shows significant role in the pollutant removal [113]. Fig. 24 shows the color removal of Congo red by ozone treatment with different pH of the initial effluent. It was found that the deterioration of dyes could take place during the alkaline conditions. In general, the ozone process can improve the efficiency of biodegradation and biodegradability of the Congo red dye.

Advantages of ozonation

- Eliminates the conventional coagulation process,
- Ensures the safer process,

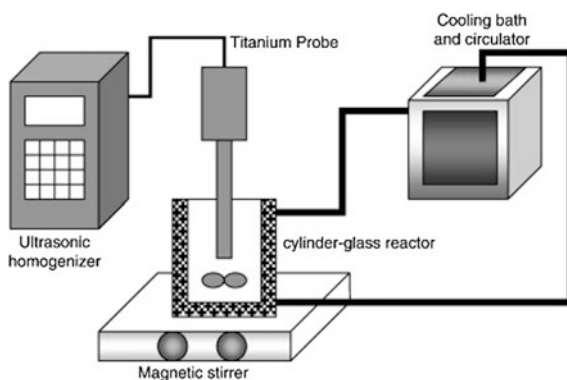
- Removes pesticides, organics, BOD, COD sewful and as well as decoloration,
- Minimizes secondary biological treatment load,
- Simple operation.

3.3.5 Ultrasonics

Chemical pollutants can be degraded by using ultrasonic technology, particularly the refractory organic pollutants in water. It also utilizes the combination of the characteristics of advanced oxidation technology, incineration, supercritical water oxidation, and other wastewater treatment technologies. Degradation speed is fast likewise the degradation conditions are also mild, its application is widely applied, and it can also be used individually or combined with other water treatment technologies. The sewage enters into the air vibration chamber after being added the selected flocculants in regulating tank which is the principle of this method. A part of organic matter in wastewater is changed into the small organic molecule by destructing its chemical bonds under the intense oscillations in nominal oscillation frequency. CODCr and the aniline concentration fall under the accelerating thermal motion of water molecules with the flocculants' flocculation rapidly companied with the color, in which it plays the role of reducing organic matter concentration in wastewater. At present, the ultrasonic technology in the research of water treatment has acquired the great achievements, but still, most of them are confined to laboratory research level [114–116]. Onat et al. [117] studied the decolorization of different reactive dyes and basic dye by the ultrasonic/microbial method. First, they treated effluents by ultrasonic then treated with microbial, ultrasonic decolorization systems are given in Fig. 25. Authors carried out the ultrasonic treatment by using ultrasonic homogenizer (Cole Parmer-CPX 600) at 20 kHz (600 W). The initial concentrations of dye solutions were 50 and 100 mg/L.

For decolorization, ultrasonic treatment was carried out for 5 h with 20 kHz; the results are significantly increased with increasing the treatment time with respect to

Fig. 25 Ultrasonic decolorization system (reprinted from [117], with the kind permission of Elsevier publications)



all three dyes. However, the decolorization is increased with decreasing the initial concentration of dyes. After 5 h, authors were obtained the results are 23, 28, and 16% for the initial concentration of effluent with 100 mg/L, whereas 31, 48, and 28% for 50 mg/L for reactive blue 4, reactive red 2, and basic yellow 2, respectively (Fig. 26).

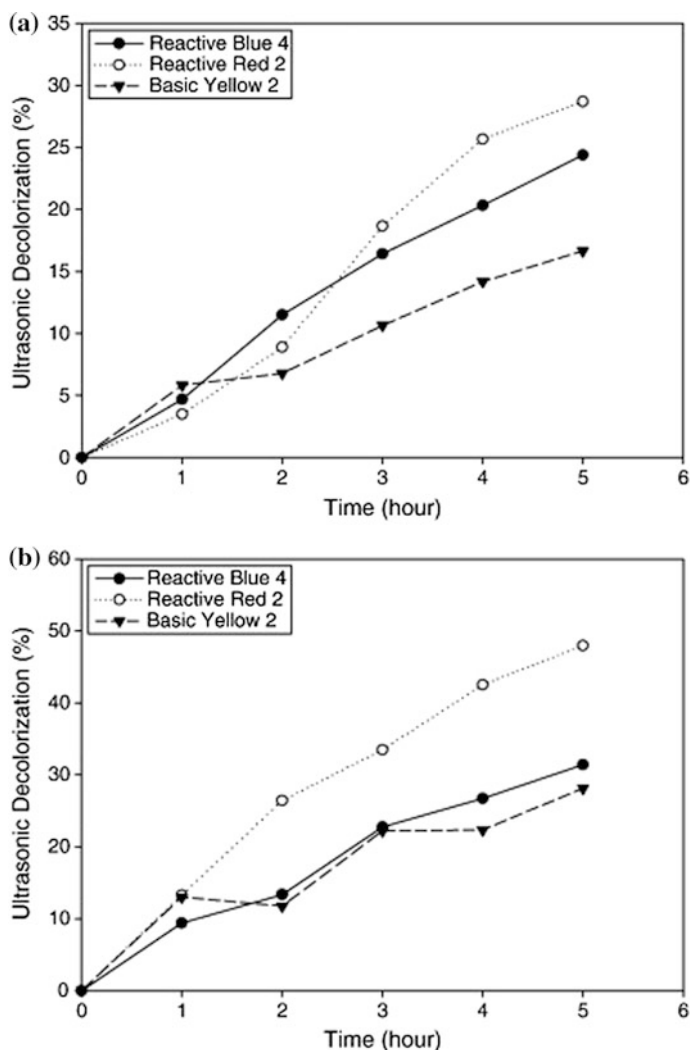


Fig. 26 Effect of ultrasonic treatment time on the decolorization of three dyes, 20 kHz. **a** 100 mg/L; and **b** 50 mg/L initial dye concentration (reprinted from [117], with the kind permission of Elsevier publications)

3.3.6 Sequencing Batch Reactor

The SBR is the modified technology of ASP. The advantages of SBR process are to control the process as well as the flexibility and alternatives of the process and its designs to achieve the latest effluent discharge standards. Initially, SBR technology was used mainly to sewage treatment, due to the technological, design feasibility and better process control that can be achieved by the modern technology makes to use SBR in much industrial wastewater treatments, including textile effluents. For the sewage treatment, SBR can save 60% of total operating expenses as compared to conventional ASP process, and it also achieves high pollutant removal efficiency. However, SBR process has disadvantages, the prime one is time consumption, it required more time, sometimes the process extends for 30 h, it is due to the slow nature of the SBR process, and it cannot manage the immediate reaction on the effluent; therefore, it is quite suitable for the small-scale industries. Generally, the operation of SBR contains five processes,

- Inflow,
- Reaction,
- Sedimentation,
- Outflow,
- Standby.

A simple schematic representation of SBR is described in the Figs. 27 and 28. It is a great resistance to the shock loading, the stored effluent can effectively resist the impact of water and other organic substance.

Sathian et al. [118] studied the effect of SBR treatment on pollutant removal efficiency for textile wastewater by simple modification of process parameters, the decolorization percentage having the good correlation with sludge retention time (SRT) as well as the air flow rate. Maximum color removal is found with the optimized process parameters.

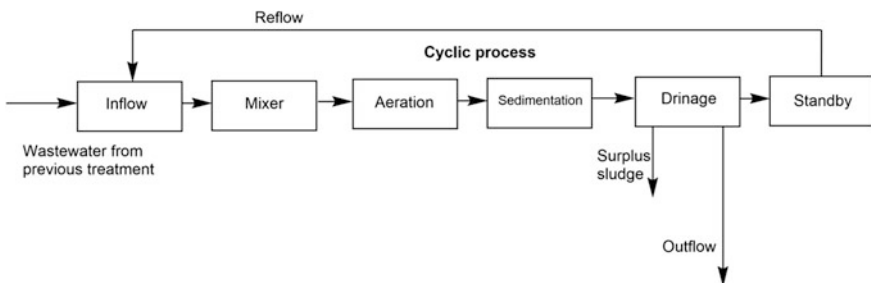


Fig. 27 Various reactions take place in SBR-based wastewater treatment process

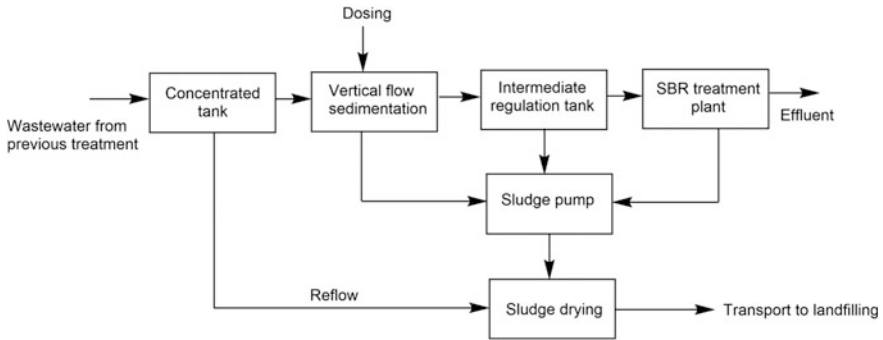


Fig. 28 SBR-based wastewater treatment process

3.3.7 Membrane Bioreactor (MBR)

Due to distinct advantages over conventional bioreactors, membrane bioreactor (MBR) technology has been used broadly for various industrial wastewater treatments. During the past decade, on evaluating the performance of MBR technology for textile wastewater, a significant number of research studies have been conducted. MBR is used in treatment of textile wastewater with a significant removal of contaminants has been investigated as a simple, reliable, and cost-effective process. However, membrane fouling is a major drawback in the operation of MBR, which leads to the decline in permeate flux and hence requires membrane cleaning. The lifespan of the membrane is eventually decreased. From MBR process, the high quality of the treated water is common to all commercial aerobic systems. A superior performance in the treatment is shown by MBR technology and operation of domestic and a wide spectrum of industrial wastewaters (including wastewater containing micropollutants) compared to other conventional treatment technologies [119]. Compared to aerobic MBR under similar operational conditions, Martin-Garcia et al. [120] reported that soluble microbial products in anaerobic MBR were 500% higher. This is one of the reasons anaerobic MBR has not been widely applied in wastewater treatment. Since the biomass characteristics are controlled by the SRT, it has an impact on membrane fouling. Generally, in increasing the mixed liquor suspended solids (MLSS) concentration is assisted by longer SRT in MBR system high concentration of MLSS are associated with the high viscosity of mixed liquor which significantly contributes to the membrane fouling has been reported by Xing et al. [121]. Figure 29 shows the schematic presentation of the laboratory-scale MBR. A bioreactor, divided into an aerobic reactor and anaerobic reactor, and an external submerged membrane module are included in the setup. An air pump controls the transmembrane pressure (TMP), pumping at a constant rate. Reversal of pressure was done in every 10 m and from the storage tank for 30 s, the membrane was back pulsed with permeate. An air compressor applied aeration along the membrane surface is used to prevent fouling on the membrane [122].

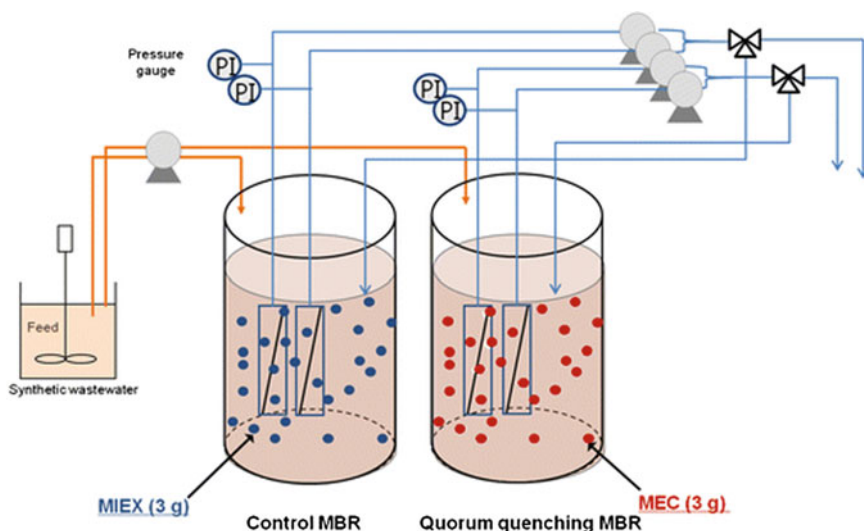


Fig. 29 Schematic presentation of the laboratory-scale MBR (reprinted from [123] Springer publications)

3.3.8 Photocatalysis

In this process, colored molecules occur as a result of initial absorption of radiation in wastewater that act as a photosensitizer. Compared to that of UV region, photosensitization is based on the utilization of longer wavelength, in order to degrade the organic compounds to CO_2 , H_2O , and mineral acid as in the existence of a suitable conductor. For the decolorization of industrial effluents, UV light has been tested in combination with H_2O_2 or solid catalyst such as TiO_2 . Due to cost, too slow, and little effective for potential full-scale application, the combination of UV/ TiO_2 seems more promising than the UV/ H_2O_2 process. During photocatalysis, electron-hole pairs are generated by TiO_2 when irradiated by the light of wavelength shorter than 380 nm. By direct hole transfer, the organic pollutants are thus oxidized or in most cases attacked by the OH radical formed in the irradiated TiO_2 . For, TiO_2 photocatalysis, the $\cdot\text{HO}$ quantum yield has been determined to be 0.040 at 365 nm. During illumination with light having energy higher than the band gap energy of semiconductor-like titanium dioxide, zinc oxide, tungsten oxide can initiate decomposition, and often the complete mineralization of organic compounds. The process is carried out under ambient conditions which is the reason for the increased interest in the photocatalytic process which can be activated by UV light and does not require expensive oxidants with the catalyst being inexpensive and non-toxic [124–126].

An ideal treatment method for the removal of color, BOD, and COD from textile wastewaters was founded to be photocatalysis by Arslan et al. [127]. Maximum efficiency by photocatalytic oxidation was observed to be achieved at pH 4. For

four non-biodegradable commercial azo dyes and one industrial wool textile wastewater using TiO_2 suspension irradiated with a medium pressure mercury lamp were investigated by photodegradation and biodegradability. In aqueous heterogeneous suspensions and in the solid state, the TiO_2/UV photocatalytic degradation of indigo and of indigo carmine has been investigated. It was observed that oxidation of dye, with almost complete mineralization of carbon, nitrogen, and sulfur heteroatoms into CO_2 , NH_4 , NO_3 , and SO_4^{2-} , was achieved in addition to prompting removal of color. Modified titanium dioxide photocatalysis removed the color completely in relatively short time (60 m) compared to that of photocatalytic oxidation of dyes in water.

Hong et al. [128] investigated the effects of photocatalysis on the color removal activity and the growth of isolated photosynthetic bacteria in batch experiment. For controlling algal adhesion and enhancing the decolorant efficiency of photosynthetic bacteria, the possibility of using thin-film photocatalysis is implicated by the results. Carneiro et al. (2004) [129] studied the photobleaching of a textile azo dye and reactive orange 16 in aqueous solution using titanium dioxide thin-film electrodes. When 100% of color removal is obtained after 20 m of photoelectrocatalysis, it is recommended to have an applied potential of +1.0 V and low dye concentration. The final step of purification of pre-treated wastewaters utilizes the photocatalytic process because it is the most effective solutions with small amount of pollutants.

3.3.9 Enzymatic Treatment

Chemical reactions based on the action of biological catalysts are involved by the enzymatic system which falls between the two traditional categories of chemical and biological processes. Specifically, target components that are detrimental to the environment can be developed by an enzymatic process. The pre-treatment step to remove one or more compounds can interfere with subsequent downstream treatment processes, and enzymatic treatment can be used. The enzymatic treatment will be most effective in those streams that have the highest concentrations of target contaminants and the lowest concentration of other contaminants that may tend to interfere with enzymatic treatment in order to that of the susceptibility of enzymes to inactivation by the presence of the other chemicals. In white rot fungal cultures, it was examined that decolorization of eight synthetic dyes including azo, anthraquinone metal complex and indigo by peroxidase catalyzed oxidation. Manganese-dependent peroxidase (MnP) did not decolorize the dyes while above 80% color was removed by ligninase-catalyzed oxidation, and further dye decolorization rate is increased linearly with ligninase dosage (Lip) [130–132].

Chrysosporium were almost completely degraded some azo and heterocyclic dyes chrysosporium in ligninolytic solution but decolorized to a different extent (0–80%) by crude ligninase. Using chicken intestine proteolytic and autolytic enzymes, enzymatic hydrolysis of tannery flushings could remove 30% of the color.

The enzymatic process promotes quick decolorization of the dye; nevertheless, maximum decolorization degree of about 30% is insignificant in relation to the decolorization degree achieved by the other processes reported by the Zamera et al. [133]. For textile dye decolorization, the enzymatic activity of four white rot fungi is as follows: *P. tremellosa*, *P. ostreatus*, *B. adusta*, and *C. vesicolor*. The ability of white rot fungi is demonstrated in this study is to produce ligninolytic enzymes, which decolorize dyes in artificial effluents. For wastewater treatment, more specifically for dye decolorization, enzyme membrane reactors are emerging recently [134, 135].

3.3.10 Radiolysis

For the treatment of textile wastewater, ionizing radiation process is one of the promising methods because the effect of radiation can be intensified in aqueous solution, in which the dye molecules are degraded effectively by the primary products formed through radiolysis of water. Radiolysis process has sufficient energy to dislodge electrons from atoms and molecules used by the radiation and to convert them to electrically charged particles called ions. Further reactions of these species will lead usually reactive and that eventually will lead to chemical reactions in the formation of free radicals [136, 137].

3.3.11 Other Processes

The effect of photocatalytic and combined anaerobic-photocatalytic treatment of textile dyes mixed wastewaters were analyzed by Harrelkas et al. [138]. Photocatalytic process based on immobilized titanium dioxide was used for this study. On both autoxidized chemically reduced azo dyes and normal dyes, the treatment was applied. The photocatalysis process was able to remove more than 90% color from crude, and autoxidized chemically reduced dye solutions were found in the result [138, 139]. Removal of UV absorbance and COD was extended up to 50% in average. A biological process consisting an anaerobic process and aerobic process in series is a promising method for treating textile wastewater which has been reported by several scientific researchers. At the first stage, the anaerobic microorganisms reduced the color and increased the biodegradability of the wastewater, and in the second stage, the reduction in the bacterial count will render the effluent more amenable to subsequent aerobic treatment in this method [140].

- Combination of advanced oxidation processes,
- Different photochemical processes,
- Photochemical/electrochemical,
- Ultrasonic and other advanced oxidation processes,
- Coagulation-based combinations,

- Adsorption-based combinations,
- Membrane-based combinations,
- Biological treatment-based combinations,
- Combination among biological processes,
- Hybrid technologies based on biological processes.

3.4 Sustainable Sludge Management

The residual, semisolid material left from textile wastewater or other industrial wastewater is referred as sludge (Fig. 30). The chemical sludge tends to have concentrations of heavy metals due to the physical–chemical processes involved in the treatment. On the other hand, biological sludge is wealthy in nutrients such as nitrogen and phosphorous along with valuable organic matter that is beneficial to depleted soils or soils focus to erosion. An environmentally sensitive problem is the treatment and disposal of sludge. Sludge production will increase subsequently with the increase in a number of wastewater treatment plants and the evolution of more stringent environmental quality standards which is the mounting global problem. The major problem of water pollution control in terms of their immediate offensive nature and potential for pollution is regarded as sludge. Due to a few environmentally unfriendly disposal routes like land disposal and direct disposal to the sea having been phased out, finding cost-effective and advanced solutions while responding to environmental, regulatory, and public pressures is the challenge faced by the sludge management. For sustainable development, the recycling and use of wastes are the preferred options rather than incineration or land filling, because of sensitivities of such contaminants like heavy metals, but sometimes it is not straightforward. The disposal of sludge always requires careful management whether it is ease or difficulty, the disposal is actually achieved, and the associated

Fig. 30 Typical sludge formed from the textile effluent



costs depends very much on circumstances. Sludge management has considerable influence by the local and national geographical, agronomic, economic, and stakeholder perception factors [141, 142].

Methods of sludge treatment

Sludge is treated to change its chemical and/or physical properties to make it fit for environmentally safe disposal options before the disposal. The quantity and properties of chemical sludge varied and it depends on the process, therefore it is required to do the stabilization process. Stabilization treatments will decrease the volume, a number of pathogenic organisms, concentrates contaminants and also diminishes odor is mainly determined by the wastewater composition, chemicals used, and treatment units. Hence, the transport of sludge is stabilized to make safe and cheaper. By conditioning and thickening, sludge can be treated to improve the effects of dewatering. On the sludge, it also has a disinfection and odor reduction effect. The four common conditioning techniques are gravity thickeners, gravity belt thickeners, dissolved air floatation, and drum thickeners, and the most common conditioning technique is chemical or thermal conditionings. Due to the cost component of chemicals, the chemical conditioning can also have a stabilizing effect as well as deodorizing. Thermal conditioning is suitable for all types of sludge. It requires energy, and there are also chances of a foul odor. To reduce water content and increase dry solid content, these methods are used. Ways to dewater the sludge have many ways in which some of them are as follows: the use of centrifuges, filter presses, recessed-plate filter presses, and a bed of reed or drying beds. Instead of dewatered, sludge can also be dried. To the sludge, the heat can be transferred either directly or indirectly through direct contact with the sludge or through a heat transfer surface. To condense and to ameliorate sludge which is produced by wastewater/effluent treatment, the biological sludge treatment is essential. Some of the treatment methods are [141–146]:

Anaerobic digestion: It is the decomposition of sludge in an anaerobic environment. The important features of anaerobic digestion are the mass reduction, methane production, and improved dewatering properties of the fermented sludge. However, for a digestion chamber, etc., it requires investment and it also has a slow degeneration rate. Pre-treatments such as thermal pre-treatment, the addition of enzymes, ozonation, chemical solubilization by acidification or alkaline hydrolysis, and mechanical sludge disintegration and ultrasound pre-treatment can be done to improve the biodegradability of sludge. By the high concentration of inhibitors such as heavy metals, temperature, etc., can also inhibit the degeneration process [147, 148].

Aerobic digestion: In the sludge, the process of oxidizing and decomposing the organic matter sludge by microorganisms in an aerobic environment is aerobic digestion. To reduce both the organic content and the volume of the sludge Aerobic sludge digestion is one process that may be used. Even though this process is sensitive to temperature, heavy metals, etc., and incurs higher energy costs, there is no useful by-product such as methane [149–151].

Enzyme treatment: To improve the hydrolysis of organic matter in sludge which limits the rate of anaerobic digestion resulting in an improvement in both biogas productions, this method is usually used as a pre-treatment of sludge and also improves the dewatering properties of the digested sludge [19].

Thermal Hydrolysis: To reduce sludge production in the sludge treatment process, thermal treatment is incorporated, anaerobic digesters and inactivate pathogens improve dewatering of sludge which enhance biogas production. In order to make sludge more readily biodegradable, this process hydrolyzes organic solids and makes them soluble. In the anaerobic digester, it also reduces the hydraulic retention time [152, 153].

Chemical stabilization: To stabilize the sludge solids, sludge is treated with chemicals in different ways in this process. Lime stabilization and chlorine stabilization are the common methods of chemical stabilization. All kinds of sludge eliminate odor and destroy pathogenic microorganisms which are stabilized by these methods. Due to their success of improving process yields, use of polyelectrolytes as a conditioner for sludge dewatering operations is also gaining popularity [19, 152, 154].

Microbial consortium: Sludge can be degraded by consortium of beneficial microbes. It can compile aerobic and/or anaerobic microorganisms. The microbial ecology of the sludge is modified by the application of microbial consortium. Maximum biological growth is achieved by the help of it, and as a result, the maximum organic matter will be consumed. BOD, COD, TSS, total and fecal coli form in all sewage and effluent generated in an industry are reduced by the microbial consortium like effective microorganism (EM). The putrefaction of sludge leading to odor reduction is suppressed by the consortium EM, and the microbes also secrete some enzymes which digest their own cell, thereby reducing the biomass/sludge. The need for use of extra chemical is also eliminated [146, 155, 156].

4 Case Studies

The case studies were conducted in the four different textile industries which are located in and around Tirupur, India. During the study, various pollutant parameters were analyzed, such as BOD, COD, TDS, TSS, other salts, minerals, color, and efficiency. The case study was conducted on daily basis for the period of 30 days to make average and tabulated (Tables from 15, 16, 17, 18 and 19), and since it is a critical issue to disclose the name of industries, it calls it as W-Z. The results of case study victimize that various pollutant parameters are reduced significantly and within their permissible limits which is suggested by central pollution control board (Fig. 31; Table 20).

Table 15 Performance of treatment system for wash water (data was collected from Textile plant “W”, at Perundurai, TN, India)

Parameters	Wash water			RO-I		RO-II	
	Inlet	Primary treatment	Ozonation	Permeate	Reject	Permeate	Reject
pH	9.7	9.65	6.87	6.12	6.84	5.85	7.09
TSS (mg/l)	177	52	21	7	74	7	128
TDS (mg/l)	3150	1944	3325	944	9978	198	18,254
BOD (mg/l)	192	45	42	1	15	2	210
COD (mg/l)	598	172	132	25	326	19	744
Total hardness (mg/l)	95	NA	NA	NA	62	Nil	1075
Chlorides (mg/l)	345	640	688	321	109	36	4511
Color %	<10	<10	Colorless	Colorless	<10	Colorless	10–20

Table 16 Characteristics of effluents in Plant “X” at Tirupur, India

Parameters	Wash water		Dye bath water			
	Inlet to ETP	Outlet	RO permeate	RO reject	Dye bath wastewater	NF reject
pH	9.8	9.82	7.5	8.17	10.38	8.17
TSS (mg/l)	47	25	BDL	45	78	62
TDS (mg/l)	4300	3650	475	21,650	39,800	48,300
BOD (mg/l)	80	65	11	460	189	100
COD (mg/l)	321	209	25	1170	897	432
Total hardness (mg/l of CaCO ₃)	344	145	3	758	98	415
Sulfate (mg/l)	85	125	7	330	175	385
Chlorine (mg/l)	1878	1698	197	10,800	20,147	26,855
Sodium (mg/l)	1750	NA	NA	9800	NA	22,500
Potassium (mg/l)	42	NA	NA	235	NA	71

Note BDL below detection limit; NA not analyzed

Table 17 Pollutant removal efficiency in common effluent treatment Plant “X” at Tirupur, India

Parameters	Pollutant removal efficiency (%)
BOD	88–98
COD	91–97
TDS	80–97
Chloride	75–97
Sodium	85–97
Nitrogen	80–92
Phosphorus	90–94

Table 18 Characteristics of effluents in Plant “Y” at Tirupur, India

Parameters	Wash water		RO stages	
	Inlet to ETP	Primary/ozonation/adsorption	Permeate	Reject
pH	9.6	9.5	7.52	8.1
TSS (mg/l)	53	21	3	49
TDS (mg/l)	3710	3655	412	20,544
BOD (mg/l)	72	55	7	295
COD (mg/l)	344	220	20	1045
Total hardness (mg/l)	192	139	0	690
Chlorides (mg/l)	1785	1777	184	10,214

Table 19 Characteristics of effluents in Plant “Z” at Tirupur, India

Parameters	Inlet effluent Inlet to ETP	Primary/adsorption	Ultrafiltration	RO stages	
				Permeate	Reject
pH	9.24	9.01	6.98	7.12	7.44
TSS (mg/l)	165	76	35	11	87
TDS (mg/l)	11,477	8445	5144	654	12,875
BOD (mg/l)	235	175	6	1	8
COD (mg/l)	568	335	84	78	114
Total hardness (mg/l)	98	NA	NA	84	2740
Chlorides (mg/l)	4870	3325	NA	235	4787
Sulfate (mg/l)	1445	815	278	18	515
Color (Hazen)	260	55	20	20	25

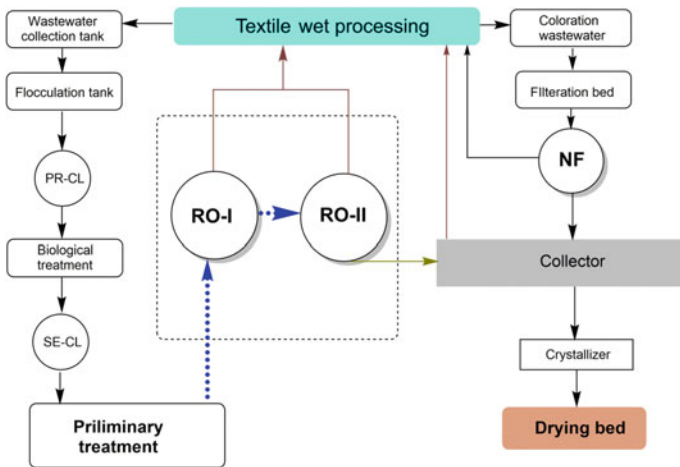


Fig. 31 Typical schematic diagram of wastewater treatment in Plant “X” at Tirupur, India (PR-CL: primary clarifier, SE-CL: secondary clarifier, RO: reverse osmosis, NF: nanofiltration)

Table 20 Characteristics of effluents in Plant “Z” at Tirupur, India, with different days

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-1	pH	8.87	6.44	7.38	6.64	8.02	8.79	8.68
	BOD (mg/L)	170	130	18	10	NA	NA	NA
	COD (mg/L)	648	392	132	82	660	NA	NA
	TDS (mg/L)	7800	8000	7600	8000	55,000	297,000	224,400
	TSS (mg/L)	168	114	40	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	7968	8114	7640	8000	NA	NA	NA
	Turbidity	77.2	48.3	4.16	0.2	0.55	NA	NA
Day-2	pH	9.46	6.50	7.46	6.95	7.90	8.77	9.03
	BOD (mg/L)	136	110	22	12	NA	NA	NA
	COD (mg/L)	584	330	115	69	640	NA	NA
	TDS (mg/L)	8900	8600	8000	7800	52,800	294,600	230,600
	TSS (mg/L)	198	124	36	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	9098	8724	8036	7800	NA	NA	NA
	Turbidity	90.5	41.5	4.7	0.19	0.58	NA	NA
Day-3	pH	10.05	6.61	7.74	6.67	7.98	9.12	9.18
	BOD (mg/L)	142	106	30	14	NA	NA	NA
	COD (mg/L)	612	390	145	93	664	NA	NA
	TDS (mg/L)	8300	8000	7600	7500	54,200	298,900	228,000
	TSS (mg/L)	174	126	42	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	8474	8126	7642	7500	NA	NA	NA
	Turbidity	84.7	55.7	5.7	0.24	0.74	NA	NA

(continued)

Table 20 (continued)

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-4	pH	10.13	6.98	7.78	6.65	8.18	9.28	9.35
	BOD (mg/L)	136	102	26	12	NA	NA	NA
	COD (mg/L)	608	385	140	91	640	NA	NA
	TDS (mg/L)	9100	8900	8400	8500	53,800	303,600	233,400
	TSS (mg/L)	168	130	48	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	9268	9030	8448	8500	NA	NA	NA
Day-5	Turbidity	77.6	46.4	6.23	0.24	NA	NA	NA
	pH	9.85	6.53	7.79	6.85	8.19	8.98	9.13
	BOD (mg/L)	160	108	38	20	NA	NA	NA
	COD (mg/L)	622	412	156	101	NA	NA	NA
	TDS (mg/L)	7800	8200	8200	8400	54,800	301,800	212,200
	TSS (mg/L)	178	102	40	<1	NA	NA	NA
Day-6	TS (TDS + TSS) (mg/L)	7978	8302	8240	8400	NA	NA	NA
	Turbidity	75	39.2	4.81	0.22	NA	NA	NA
	pH	10.18	6.80	7.99	6.88	8.15	8.91	9.05
	BOD (mg/L)	150	136	32	12	NA	NA	NA
	COD (mg/L)	610	390	140	92	NA	NA	NA
	TDS (mg/L)	8800	9000	9000	8800	55,800	295,200	225,400
Day-6	TSS (mg/L)	148	86	34	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	8948	9086	9034	8800	NA	NA	NA
	Turbidity	68.2	34.3	4.05	0.26	NA	NA	NA

(continued)

Table 20 (continued)

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-7	pH	9.88	6.85	7.98	6.94	8.15	9.38	9.45
	BOD (mg/L)	130	100	30	18	NA	NA	NA
	COD (mg/L)	544	340	124	78	668	NA	NA
	TDS (mg/L)	8400	8600	8400	8600	54,800	296,800	216,800
	TSS (mg/L)	270	148	38	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	8670	8748	8438	8600	NA	NA	NA
	Turbidity	123	56.4	4.02	0.36	0.68	NA	NA
Day-8	pH	10.00	6.89	7.88	6.82	8.27	9.23	9.39
	BOD (mg/L)	110	96	24	10	NA	NA	NA
	COD (mg/L)	510	305	108	73	NA	NA	NA
	TDS (mg/L)	8400	8500	8400	8400	56,400	294,300	219,600
	TSS (mg/L)	288	136	60	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	8688	8636	8460	8400	NA	NA	NA
	Turbidity	130	40.4	8.43	0.34	0.63	NA	NA
Day-9	pH	9.99	7.02	7.85	6.98	8.05	9.15	9.25
	BOD (mg/L)	120	90	20	10	NA	NA	NA
	COD (mg/L)	496	304	115	77	610	NA	NA
	TDS (mg/L)	8900	9100	8500	8700	53,400	293,600	220,600
	TSS (mg/L)	248	112	30	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	9148	9212	8530	8700	NA	NA	NA
	Turbidity	103	40.1	3.99	0.26	0.4	NA	NA

(continued)

Table 20 (continued)

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-10	pH	10.18	6.52	7.85	6.61	8.15	9.15	9.21
	BOD (mg/L)	102	80	10	Nil	NA	NA	NA
	COD (mg/L)	480	280	86	53	540	NA	NA
	TDS (mg/L)	7400	7600	7500	8100	54,200	296,800	219,200
	TSS (mg/L)	184	98	42	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	7584	7698	7542	8100	NA	NA	NA
	Turbidity	86	39.3	6.98	0.28	0.66	NA	NA
Day-11	pH	9.59	6.62	7.61	6.59	7.86	9.11	9.15
	BOD (mg/L)	120	70	26	12	NA	NA	NA
	COD (mg/L)	568	352	130	84	NA	NA	NA
	TDS (mg/L)	7000	7400	7000	7600	54,700	297,100	227,300
	TSS (mg/L)	176	78	48	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	7176	7478	7048	7600	NA	NA	NA
	Turbidity	86.8	26.4	6.48	0.31	NA	NA	NA
Day-12	pH	8.98	6.38	7.78	6.51	7.79	9.07	9.21
	BOD (mg/L)	104	80	22	12	NA	NA	NA
	COD (mg/L)	502	315	105	68	NA	NA	NA
	TDS (mg/L)	7200	7400	7600	7800	55,300	299,200	226,100
	TSS (mg/L)	170	96	47	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	7370	7496	7664	7800	NA	NA	NA
	Turbidity	76.4	37.3	9.6	0.29	NA	NA	NA

(continued)

Table 20 (continued)

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-13	pH	9.45	6.81	7.66	6.58	8.14	8.54	8.58
	BOD (mg/L)	160	114	44	22	NA	NA	NA
	COD (mg/L)	696	394	139	92	NA	NA	NA
	TDS (mg/L)	9800	9200	8600	8300	56,400	298,800	216,400
	TSS (mg/L)	238	98	50	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	10,038	9298	8650	8300	NA	NA	NA
	Turbidity	103	39.4	7.15	0.31	NA	NA	NA
	pH	8.93	6.52	7.51	6.48	7.75	8.64	8.48
	BOD (mg/L)	Under test	Under test	Under test	Under test	NA	NA	NA
	COD (mg/L)	728	424	144	92	NA	NA	NA
Day-14	TDS (mg/L)	8800	9400	8600	8200	54,300	299,800	218,600
	TSS (mg/L)	234	104	46	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	9034	9504	8646	8200	NA	NA	NA
	Turbidity	110	39.8	6.31	0.31	NA	NA	NA
	pH	8.39	6.23	7.79	6.95	7.85	8.95	8.82
	BOD (mg/L)	Under test	Under test	Under test	Under test	NA	NA	NA
	COD (mg/L)	720	435	156	101	NA	NA	NA
	TDS (mg/L)	8600	9000	9100	8900	53,200	298,600	214,600
	TSS (mg/L)	238	118	47	<1	NA	NA	NA
		8838	9118	9147	8900	NA	NA	NA

(continued)

Table 20 (continued)

Day	Parameters	ETP feed	Primary clarifier outlet	Secondary clarifier outlet	RO-1 feed	Evaporator-I feed	Crystallizer feed	Evaporator-II feed
Day-16	TS (TDS + TSS) (mg/L)							
	Turbidity	110	41.4	9.1	0.31	NA	NA	NA
	pH	9.34	6.67	7.78	6.48	8.11	9.32	9.18
	BOD (mg/L)	Under test	Under test	Under test	Under test	NA	NA	NA
	COD (mg/L)	560	355	128	81	NA	NA	NA
	TDS (mg/L)	9100	9000	8800	8800	54,600	298,600	216,200
	TSS (mg/L)	148	102	51	<1	NA	NA	NA
	TS (TDS + TSS) (mg/L)	9248	9102	8851	8800	NA	NA	NA
	Turbidity	64.2	29	11	0.35	NA	NA	NA

5 Conclusions

This chapter summarized the various types of sustainable wastewater treatments for textile industry, and also it described the environmental hazards associated with conventional wastewater treatment techniques. This chapter clearly depicted the different characteristics, such as BOD, COD, TDS, TSS, turbidity, and pH variation of pollution caused by the each stage of textile processing with respect to utilization various chemicals and auxiliaries. The various sustainable wastewater treatment techniques like AC adsorption, AOP, electrocoagulant, membrane technology, ultrasonic associated effluent treatments, photocatalysis, SBR/MBR are reviewed deeply with their pros and cons as well as their pollutant removal efficiency. Generally, the AC adsorption and ozonation treatments are used to prepare the effluent for membrane filtration technique to get adequate process efficiency. Use of multiple effect evaporation system could play vital role to reduce the effluent volume. The multiple effect evaporation techniques can help to recover the glauber salt and other residual substances. Recently, the reuse of effluent treated water is assumed significant importance, due to scarcity of water resources and increasingly stringent regulatory requirements for the disposal of the effluent. However, reuse or recycle of wastewater depends on the selection of effluent treatment process.

5.1 *Recommendations for Effluent Management in Textile Industries*

Textile industry treated the effluent to segregate the water and other substance; generally the recovery of water is quite easy than the salt or other residues. It is better to treat the highly polluting effluents such as dye bath discharge; however, it is 10% of total effluent discharge, and remaining 90% are from low-polluting streams like wash water. Segregation of these streams makes huge difference in the effluent treatment, since low-polluting streams have nominal dissolved solids, heavy metals, and other pollutant materials. Sustainable wastewater treatment can be appropriately applied on both the effluent streams; however, the sustainable wastewater treatments have the scope to recover and recycle the water and other substances. For the effective effluent treatment for textile industries, there are some recommendations,

- High pollutant effluent stream can be treated separately, when it mixed with low pollutant streams, it makes difficult in the treatment and it increases the overall cost.
- The reject of EC, RO, NF should be treated with high pollutant effluent stream.
- Utilize maximum to sustainable wastewater treatment, since it produces less residue (sludge).

- Sustainable wastewater treatment has no compliance with respect to the norms and standards.
- Combination of two or more processes (i.e., EC/Membrane filtration) makes better pollutant removal efficiency.

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