22 Advanced and Ecofriendly Technologies for the Treatment of Industrial Wastewater to Constrain Environmental Pollution

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Abstract

The environmental contamination in the present situation is of great importance to industrial wastewater. Industries consume huge amounts of water and toxic chemicals during product formation and generate large amounts of wastewater loaded with toxic and lethal pollutants, which discharge into the environment without proper treatment and cause major threat to receiving ecosystem. The discharged wastewaters are often characterized by high BOD, COD, TDS, heavy metals, phenolics, and organic and inorganic materials. The conventional wastewater treatment is not efficient to remove these pollutants due to its low biodegradability and toxicity. Several physicochemical methods are available that have been employed for the treatment of wastewater. However, at industrial scale the application of these processes is not suitable due to high cost. Alternatively, nowadays biological treatment process has been considered because of its low charge, energy consumption, and environment-friendly nature. Therefore, the chapter provides updated information of industrial wastewater and their characteristics. Besides this, the chapter also describes various biological treatment processes of industrial wastewater.

Keywords

Industrial wastewater · Environmental pollution · Biodegradation · Toxicity

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22.1 Introduction

The modern life and environment are continuously affected by the involvement of industrial development that discharge huge amounts of noxious and lethal pollutants containing wastewaters into the environment. The rapid industrial activities like paper, tannery, distillery, textile, pharmaceuticals, etc., are polluting drinking water consumed by animals and humans in their daily routine. The wastewaters generated from these industries encumbered with various toxic pollutants including organics, phenolics, dyes, metals and inorganic pollutants, etc., which enter into the environment and cause hazardous effect on aquatic flora and fauna (Haq et al. 2016a, b, c; Raj et al. 2014a, b). Massive production and discharge of untreated industrial wastewater (IWW) are continuously contaminating natural resources and posing a significant challenge to the preservation of a clean and healthy ecosystem (Gricic et al. 2009). The usual management of wastewater including physicochemical process is employed for the management of wastewater (Narmadha and Kavitha 2012; Shivajirao 2012). However, due to their high cost and energy requirements, these methods are not ideal at industrial level. Thus, there is an urgent need of advanced and sophisticated technologies being developed, which should be compatible at industrial level. Because of their low cost and eco-friendliness, many biological wastewater treatment systems are used for IWW remediation, and they are likely to be much more proficient in waste disposal (Rajasulochana and Preethy 2016; Haq and Raj 2020). Therefore, this chapter provides updated information regarding industrial wastewater, their contaminants, and treatment process for sufficient management of wastewater before disposal into the environment.

22.2 Industrial Wastewater and Their Contamination in Environment

Huge amounts of various chemicals are used in factories, mills, and industries for product formation, resulting in the production of huge quantity of toxic and hazardous wastewater that are released without proper treatment into the environment (Dsikowitzky and Schwarzbauer 2013; Haq et al. 2017, 2018). The waste generated from industries is divided into two main categories such as biodegradable and nonbiodegradable on the basis of their nature. Households, textile, distilleries, leather, fruit, and paper processing industries can produce biodegradable waste that can be transformed or disintegrated into nontoxic products with the aid of microbial system. Nonbiodegradable waste, on the other hand, is waste that cannot be degraded by microorganisms, which is created by plastic, glass factories, fertilizers, iron and steel industries, nuclear operations, pharmaceutical and drug industries, and is fully harmful, causing environmental contamination and life-threatening disease to living organisms. Because of their harmful and unsafe consequences, this type of hazardous waste necessitates the use of appropriate management treatment technologies. Some of the most toxic industries that release their wastewater in environment are discussed here.

22.2.1 Pulp and Paper Industry

Pulp and paper industry is globally one of the topmost socioeconomic sectors and plays a key role in economic growth. Paper industry uses plant materials and huge amounts of water and chemicals for paper production. The chemicals that are used in the paper industries are highly toxic and rich in persistent organic pollutants (POPs), creating a major hazard to the environment. The paper industry is a highly water-utilizing industry and requires enormous quantity of water: 4000–12,000 gallons per ton of pulp (Ince et al. 2011). It is estimated that about 75% of consumed water during paper production is discharging as wastewater (Yadav and Garg 2011). The pulp and paper production involve mainly two key steps, namely, pulping followed by bleaching. These two process are highly water consuming and wastewater generated during these steps loaded with highly toxic contaminants. A large amount of various chemicals, such as sodium hydroxide, sodium carbonates, sodium sulfide, bisulfites, elemental chlorine or chlorine dioxide, calcium oxide, hydrochloric acid, and so on, are used in the paper manufacturing process, consequently in the creation of massive amounts of wastewater filled with organic and inorganic salts and radioactive contaminants, which are released after unfinished management (Haq and Raj 2020). During pulp and paper production process, industry release large amount of wastewater containing high concentration of toxic processing chemicals, which is characterized by high BOD, COD, phenolics, metals, and dark brown color of the effluent. The discharged effluent from the paper industry is highly toxic and poses threat to aquatic flora and fauna (EPA 2002). The effluent is loaded with organic and chlorinated hydrocarbons, and organic absorbable halides (AOXs), which affect people and animals in the atmosphere. Different chemicals from the paper industries are gathered through the food chain and are impossible to break down because of the chemical complexity and reactivity. These contaminants are extremely damaging and can lead to serious health and impairments, including neurological, neuronal, and carcinogenic problems (Ince et al. 2011).

22.2.2 Tannery Industry

The tannery industry has been categorized as a red category industry and is tremendously contaminating the environment by discharge of contaminated effluent during lather production. Tanning industry is a major contributor to a country's socioeconomic equity due to its large export and job opportunities (Kumari et al. 2014, 2016). The tannery industry consume large quantities of freshwater (~35–40 L) for the processing of raw skin/hides and utilize huge amounts of toxic chemicals for the exchange of hides into precious products. During the production of lather, this industry discharges huge amounts of wastewater loaded with toxic and lethal contaminants, which are discharged into the environment, posing threat to aquatic animals and human being (Kumari et al. 2014, 2016; Haq and Raj 2018). Substantial sulfates, chlorides, suspended components, toxic metals (mainly chrome), colored complexes, and other contaminants are included in wastewater produced by the tanneries industry (Kumari et al. 2016; Raj et al. 2014b). But the chrome emission is caused mostly by the tanning industry as chrome tanning is used for inexpensive leather manufacturing. The tannery effluents, which make the essential body structure, are serious carcinogenic and transmutagenic changes and are highly toxic to marine and human life ecology (Kumari et al. 2016; Haq and Raj 2018). High chromium toxicity is significantly harmful and has detrimental consequences for living organisms (Kumari et al. 2014; Raj et al. 2014b).

22.2.3 Distillery Industry

Due to its widespread use in pesticides, pharmaceutics, cosmetics, food and perfumery industries, etc., alcohol manufacturing industries are growing considerably. The distillery are highly water-consuming and pollution-causing industry and manufacturing ~8–15 L wastewater/L of overall liquor generation. It is estimated that in India alone there are about 300 distillery industries that are accountable for the production of about 40 billion liters of wastewater annually (CPCB Central Pollution Control Board 2011). In general, molasses is used as a major raw material in the distiller industry, producing waste known as molasses-spent wash (MSW). The main problem of MSW is the presence of melanoidins, organics, and low biodegradability causing severe environmental pollution. The distillery effluent is described by their brown color due to melanoidins (a recalcitrant compound), acidic pH (3–5), elevated COD (80,000–160,000 mg/L), organic and inorganic compounds, phenolic compound, and mineral salt (Basu et al. 2015; Mohana et al. 2009). Due to high pollution load and improper treatment of distillery industry wastewater, it directs to elevated height of water and soil pollution, eutrophication of stream, and inhibition of photosynthesis due to dark brown color of effluent. Due to acid nature of distillery wastewater, it causes reduction of soil alkalinity and deficiency of manganese ion, which leads to soil infertility, seed germination inhibition, and also damage the agricultural crops. Due to the presence of putrified organics, sulfur, and phenolic compounds, the considerable amount of wastewater generated by distilleries indicates fatalities to microbial communities, fishes, and other planktons due to the presence of poisonous and permanent contaminants, which can become harmful for the marine and soil ecosystems.

22.3 Advance Wastewater Treatment Technologies

22.3.1 Biological Treatment

Biological remediation is an ecofriendly method used for the detoxification of wastewater having organic and inorganic toxins using microorganisms such as microbes, fungi, algae, and enzymes (Kumar et al. 2017a, b, c; Haq et al. 2017, 2018; Haq and Raj 2018, 2020). In bioremediation process, complex toxic waste material is converted into simpler less/nontoxic compounds, therefore, direct to mineralization and detoxification (Reshma et al. 2011; Singh et al. 2014). The process of bioremediation mainly depends on the catabolic capability of microorganism to degrade the pollutants, which is also affected by the accessibility of pollutants and their bioavailability (Antizar-Ladislao 2010). Bioremediation technique involves various techniques like bioattenuation, biostimulation, and bioaugmentation (Maszenan et al. 2011). Various literatures are accessible on the topic of bioremediation and biodegradation of industrial wastewater by means of single microbe and their consortia (Singh et al. 2011; Megharaj et al. 2011; Maszenan et al. 2011; Paisio et al. 2012; Haq et al. 2016a).

Bioremediation of paper industry wastewater using bacterial spp. has been employed, and some of the bacterial cultures are available commercially for this purpose. Large number of bacterial spp. (*Micrococcus luteus*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Pseudomonas putida*, *Acinetobacter calcoaceticus*, *Ancylobacter*, *Bacillus cereus*, *Citrobater*, *Methylobacterium*, *Enterobacter*) were used for the treatment at small scale and they recorded color reduction (50–97%), BOD (80–96%), COD (80–97%), and lignin (50–97%) (Tyagi et al. 2014; Tiku et al. 2010; Raj et al. 2007). Similarly, several researchers have reported that individual or consortia of bacteria have the potential to degrade kraft lignin as well as its derivatives produced from diverse pulping processes (Chandra et al. 2011; Chandra and Bharagava 2013). The study of Chandra and Singh (2012) suggested that during bioremediation of paper mill effluent using consortium of bacteria (*Pseudochrobactrum glaciale*, *Providencia rettgeri*, and *Pantoea* sp.) the ligninolytic enzyme (LiP, Lac, and MnP) induction was observed. Within 216 h after treatment, the bacterial consortia successfully eliminated lignin and chlorophenol (90%). Raj et al. (2014a) and Haq et al. (2016a, b, c) confirmed generation of laccase and lignin peroxidase enzyme during the degradation of paper industry wastewater by *Paenibacillus* sp. and *Serratia liquefaciens,* respectively. In addition to color and lignin, the bacterial treatment methods also eliminate the effluent BOD and COD. Bioremediation of tannery effluent has been performed by many workers (Kumari et al. 2016). The study of Kim et al. (2014) reports the reduction of COD (98.3%) and Cr (88.5%) from tannery wastewater (TWW). In another study, the reductions in Cr, BOD, and COD were 63.8% and 90%, respectively, using *E. coli* and reductions in Cr, BOD, and COD were 73.5% and 95.4%, respectively, using *Bacillus* sp. during the treatment of tannery wastewater (Noorjahan 2014). Yusuf et al. (2013) reported removal of 85.2% of COD using *P. fragi* and 87.6% of COD using *B. subtilis* and from tannery effluent. El-Bestawy et al. (2013) used the consortium of five different bacterial spp. for the removal of COD (79.16%), BOD (94.14%), and Cr (93.66) from tannery effluent. The consortium of bacterial spp. (*P. aeruginosa, B. flexus, E. homiense,* and *S. aureus*) reduced 80% COD from wastewater of tannery industry. The bioremediation of distillery wastewater (DWW) using bacterial system has been performed by many researchers. Kaushik and Thakur (2009) isolated five separate bacterial strains from polluted distillery wastewater sites in order to evaluate COD and color elimination of wastewater for distillery wastewater degradation analysis.

The one bacterium (*Bacillus* sp.) of the five bacterial spp. was able to reduce COD (30%) and color (21%) significantly from distillery wastewater. After optimization of various environmental and physiological factors by Taguchi approach, the reduction of COD and color was increased up to 90% and 85%, respectively, by *Bacillus* sp. within 12 h of incubation period. In another study, David et al. (2015) found the bacterium *Pseudomonas aeruginosa* to have the efficiency to remove the color (92.77%) from DWW and while producing polyhydroxy butyrate in the presence of excess carbohydrate source. Melanoidins, a recalcitrant organic pollutant present in DWW, are the main coloring agent of effluent that are tough to be degraded by natural treatment system. Santal et al. (2016) isolated and identified a bacterium known as *Paracoccus pantotrophus* for the evaluation of melanoidins degradation. They found that the bacterium has the potential to decolorize melanoidins up to $81.2 \pm 2.43\%$ with aid of glucose and NH_4NO_3 as carbon and nitrogen sources. Further, Krzywonos et al. (2017) used *Bacillus megaterium* ATCC 14581 for color removal study. After optimization of organic and inorganic nutrient source, the bacterium was able to remove 38% color of the DWW. In other study, Georgiou et al. (2016) immobilized the ligninolytic Lac using two different matrices as alumina or controlled pore glass-uncoated particles and found the distiller wastewater decolorization percent as 71% and 74%, respectively, after 2 days of incubation period. In the study of Chen et al. (2013), they reported the combined biological process with microelectrolysis can achieve 97.1% color reduction from distillery wastewater. The result of this study also showed the important role played by ligninolytic enzyme and fungal biomass during decolorization process.

22.3.2 Phytoremediation

Phytoremediation is an ecofriendly and low-cost treatment technology. Phytoremediation is beneficial for the environment over the physicochemical cleanup methods that require chemicals, high cost, energy, disturbance of soil structure, and microflora. Phytoremediation is a technique that involves the association between plants and microbes for the removal of contaminants to preserve the health of living organisms and environment. It requires a different strategy for removing metal pollutant from polluted areas, for example, phytoextraction, psycho-stabilization, phytostimulation, phytovolatization, and rhizofiltration (Lee et al. 2013; Chirakkara et al. 2016). There are several articles present on phytoremediation and phytoremediation of municipal wastewater pollution.

Phytoremediation of paper mill pollutants has been reported by many workers like Kumar and Chopra (2016), who used water caltrop (*Trapa natans*) for the reduction of pollution load of paper mill effluent through phytoremediation technique. The result of the study showed that water caltrop (*T. natans*) have the potential to remove TDS, BOD, COD, TKN, and metals like Ca^{2+}, Mg^{2+} and K^+, Cd, Cu, Fe, Ni, Pb, and Zn of the paper mill effluent after the phytoremediation. In the study of Das and Mazumdar (2016), they reported that the plant *Salvinia cucullata* can reduce BOD, COD, TS, TSS, TDS, P, hardness and chloride, and several heavy metals (Cd, Cu, Cr, Ni, Pb, Mg, Mn, Fe, and Zn) present in paper mill effluent. Kumar et al. (2014) also proved the removal efficiency of plant *Croton sparsiflorus* for the treatment of pulp wastewater as it can remove the heavy metals such as Pb, Cr, Cd, and Zn. Johnson et al. (2019) studied the treatment of pulp and paper mill industrial effluent by phytoremediation using *Ludwigia abyssinica*, *Hydrolea glabra,* and *Ceratophyllum demersum*. The results of the study showed that *Ludwigia abyssinica* was highly efficient in the removal of Pb, Cr, Mn, and Zn, BOD, and COD as it was reduced to 69.42%, 64.60%, 80.40%, 57.48%, 82.09%, and 77.77%, respectively. Secondly, *Hydrolea glabra* has the potential to remove these parameters in terms of percentage as 54.85%, 52.10%, 53.30%, 54.99%, 76.12%, and 58.73%. *Ceratophyllum demersum* was less efficient compared to both plants, but it also reduces the pollutants significantly as 38.83%, 35.60%, 31.20%, 52.49%, 65.67%, and 57.67%, respectively.

Gupta et al. (2018) treated tannery wastewater contaminated soil using microbial-associated phytoremediation process. For treatment, Cr6+-resistant PGP *Pseudomonas* sp. (CPSB21 strain) were isolated from the effluent polluted soil. They applied the bacterium for the evaluation of Cr^{6+} toxicity reduction in soil. The result of the study showed that after bacterial treatment the toxicity of the soil was reduced and the growth of the sunflower plant grown in soil was increased due to enhanced nutrient uptake during pot experiment. In another study, Kassaye et al. (2017) used papyrus (*Cyperus papyrus*), Para grass (*Brachiaria mutica*), and swamp smartweed (*Polygonum coccineum*) for the treatment of TWW. The study's results indicate that the Cr present in TWW was shifted to root and shoot of plants from TWW. The Cr removal efficiency of the Para grass and papyrus was high compared to swamp smartweed from TWW. The bacterial-aided phytoremediation of organic contaminants in TWW from a traditional wastewater tanning plant has been documented by Gregorio et al. (2015).

The problems associated with distillery wastewater and a detailed study of existing biological treatment approaches have been reviewed by Kharayat (2012). Billore et al. (2001) used *Typha latipholia* and *Phragmites karka* for the treatment of distillery effluent and the result showed 64%, 85%, 42%, and 79% reduction in COD, BOD, total solids, and phosphorus, respectively. One of the categories of phytoremediation, known as phytoextraction, has been used for the removal of heavy metals from soil, which are essential for plant growth (Fe, Mn, Zn, Cu, Mg, Mo, and Ni). Some of the metals like Cd, Cr, Pb, Co, Ag, Se, and Hg with unknown biological function can also be accumulated (Cho-Ruk et al. 2006). Hegazy et al. (2009) reported the bioaccumulations of the four heavy metals like Cr, Cu, Pb, and Zn using *Lemna gibba* (duckweed)-contaminated industrial wastewater. The result of the study showed that *L. gibba* has the potential to accumulate the heavy metals and was ranked as Zn came in the first place followed by Cr, Pb, and Cu with bioaccumulation factors 13.9, 6.3, 5.5, and 2.5, respectively.

22.3.3 Electrokinetic Phytoremediation

The combination of phytoremediation with electrokinetics known as electrokinetic phytoremediation could be a promising approach for the remediation of metals in contaminated soil and wastewater (Saxena et al. 2020). The study of Mao et al. (2016) showed the removal of heavy metals from paddy soil using electrokinetic phytoremediation approaches. The findings show that the electrokinetic field (EKF) greatly increases the absorption of As and Cs in roots and shootings of the plant and thus increases the efficacy of phytoremediation. The use of electrokinetic phytoremediation for pollutant removal is the latest approach in this field and needs atomization of different parameters such as current application, intensity of electrical field, time period, etc., and their effect on pollutants removal is still a challenge (Mao et al. 2016). Further, the use of mixed pollutants (organic and inorganic) and electrical kinetic phytoremediation has also not been identified.

22.3.4 Microbial Fuel Cells

Microbial fuel cell (MFC) is a new and suitable technology for the treatment of industrial wastewaters. MCF is a bioelectrochemical system that utilizes microorganism for the conversion of organic pollutant into electrical energy. The use of electricity and excess sludge generation may be an effective replacement for traditional activated sludge treatment. MFCs have many advantages over conventional energy systems (such as direct generation of electricity, energy savings due to anaerobic treatment, low slot yield), environmental benefits (water recovery, low carbon footprint, reduced slot generation), economic benefits (power and value-added chemicals), and low operational costs and operating cost (self-generation of microorganisms, good resistance to environmental stress, and amenable to real-time monitoring and control) (Li et al. 2010; Gude 2016). MFCs are ecofriendly technologies for organic substrate electricity manufacturing in industrial wastewater that are free of processes downstream and work under mild operational conditions especially at ambient temperatures (Gude 2016). Primary sludge or processed wastewater was projected to contain 1.43 kWh/m^3 or 1.8 kWh/m^3 using MCFs, respectively (Ge et al. 2015). MFCs consume only about one order of aerobic processes on sludge basis (~0.3 kW or €0.6 kWh/kg of COD in average) of 0.024 kW, or 0.076 kWh/kg COD (primarily for feeding and blending the reactor) (Zhang et al. 2013a, b). This implies, in relation to traditional activated sludge processes that display great energy savings and potential for energy recovery from waste water treatment, that the MFCs consume only approximately 10% of external energy (Gude 2016).

22.4 Challenges and Future Prospects

Each and every industry faces challenges during wastewater treatment process in which the key issues are cost of treatment system, energy consumption, and safe disposal of waste. The degradation/detoxification of pollutants present in industrial wastewater is a serious concern and requires an appropriate treatment technology to remove the toxic contaminants for the safeguard of environment. In our previous articles, we have described various physicochemical and biological treatment technologies for wastewater treatment process (Haq and Raj 2018, 2020). Biological treatment system with its various aspects has emerged as a low-cost and ecofriendly system compared to conventional and other physicochemical processes that are costly and environmentally destructive. However, bioremediation also has some restriction, which involves low level of pollutant to microbes or high concentration of toxic compound that inhibit the microorganism and plants, inhibition of enzymatic system that is responsible for degradation, and many more.

To elaborate the future scope of the bioremediation, the research should be done on the following topics:

1. Isolation and identification of highly potential microorganism for the degradation of ROPs
2. Identification of prominent carbolic gene responsible for efficient enzyme production to enhance the degradation/detoxification of environmental pollutants
3. Development by recombination DNA technology (RDT) for successful bio- and phytoremediation of transgenic microorganisms and of plants
4. Use of appropriate plant species for phytoremediation.
5. Investigation of new rhizobacteria and endophytes for microbe-assisted phytoremediation.

But attempts remain in order, including phytoremediation on the ground, to achieve economic viability of bioremediation technologies.

22.5 Conclusions

On the basis of available literature, finally it is concluded that the wastewater of industrial origin is a chief source of toxic and hazardous pollutant that contaminates the environment. Therefore, industrial wastewater treatment system requires a cost-effective and environmental-friendly treatment technique that treats industrial wastewater holistically. In addition of this, the literature also shows that biological treatment system (microorganism and plants) is a promising approach for the removal of contaminants of industrial wastewater. But still there is gap of knowledge regarding the health hazard of industrial wastewater on aquatic and terrestrial ecosystem. In addition, it seems that priority should be paid to limiting and providing appropriate solutions for the current care environment. Therefore, this chapter includes comprehensive information on industrial wastewater, its characteristics, and environmental processing technologies.

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