3 Need for the Advanced Technologies for Wastewater Treatment

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Abstract

Water is one of the basic needs of a living organism to sustain life on earth. But due to the rapidly increasing population, urbanization, and industrialization, the quality of portable water is depleting. If the wastewater is not treated efficiently, then it generates a number of problems such as malodor and health problems, gives birth to disease-causing agents, etc. Therefore, it is the need of the day to develop some new techniques which are more efficient in treating the wastewater. In this chapter, the use of new techniques such as membrane bioreactor, advanced oxidation techniques and nanotechnology for the treatment of wastewater have been discussed. The nanocomponents such as nanosorbents, nanocatalysts, molecularly imprinted polymers (MIPs), and nanostructured catalytic membranes (NCMs) are the recent techniques which treat wastewater very efficiently. The water recovered after these treatments meet the human consumption criteria.

Keywords

Wastewater • Nanoparticles • Advanced oxidation technologies • Membrane bioreactors

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R. Kumar et al. (eds.), *Advances in Environmental Biotechnology*,
DOI 10.1007/978-981-10-4041-2_3

3.1 Introduction

Waste is generated by mankind in all forms: water emulsions and solid wastes. Wastewater is defined as the residual water containing the waste of the institutes, residential, industrial, commercial and agricultural community after it has been used for a number of purposes. If the wastewater is allowed to accumulate, it will lead to various problems such as the production of malodorous gases, human gut infection etc. This is so because the wastewater contains a number of pathogenic microorganisms and increased growth of aquatic plants (eutrophication). It may also contain certain mutagenic or carcinogenic compounds. Therefore, it is very necessary to treat wastewater, remove the pollutants, reuse and safely discharge the residual water in the rivers. Population, urbanization and industrialization are causing stress on the freshwater resources which have created an alarm to search for new technologies which could treat the wastewater and make it available for human consumption. Rio Earth Summit (1992) introduced the concept of recycle, reuse and recovery for the sustainable development. The conventional wastewater treatment technologies that have been used do not treat the water to that extent which can be used for human use. A lot of water for domestic use is wasted in gardening, flushing and cleaning. For the purpose of gardening and flushing, the recycled water can be used (Ngo et al. 2007).

3.1.1 Conventional Treatment Technologies

To improve the quality of wastewater by removing nutrients, solids, and organic matter, water is given preliminary, primary, and secondary treatments. These processes are explained below:

3.1.1.1 Preliminary Treatment

In the preliminary treatment, the wastewater is screened for any debris and their separation. Sticks, toys, rags, leaves, sand, food particles and gravels are removed from the water using grit chambers, bar screens and comminutors. The separated out debris are then disposed of in a landfill.

3.1.1.2 Primary Treatment

Primary treatment involves sedimentation and skimming for the removal of inorganic and organic materials. The floatable materials are skimmed off the wastewater. The heavy metals associated with solids, organic nitrogen and phosphorous are removed, but the dissolved solids remain unaffected. During the primary treatment, around 65% of oil and grease, 50–70% total suspended solids and 25–50% BOD are removed.

3.1.1.3 Secondary Treatment

The effluent from the primary treatment is subjected to aerobic processes for the removal of remaining organic matter and suspended solids. The aerobic biological treatments involve the decomposition of organic matter into inorganic compounds such as CO_2, NH_3 etc. in the presence of aerobic microorganisms.

3.2 Need for Advanced Wastewater Treatment Technologies

Since the past two decades, the efficiency of conventional wastewater treatment process has been reduced due to the three major factors (Langlais et al. 1991; Mallevialle et al. 1996): (1) population, (2) awareness, and (3) industrialization.

3.2.1 Population

With the rapid increase in the population, the water resources are depleting at alarming rates. The municipal and industrial wastewater need to be treated to remove the pollutants so that it may be reused. This treatment becomes more important in the semiarid and arid regions where a lot of money is spent on the import of the irrigation and portable water. The conditions are made worse by the release of toxic compounds in the water. These problems can be solved using the advanced wastewater treatment technologies which help in the removal of harmful compounds much more efficiently than the conventional wastewater treatment technologies.

3.2.2 Awareness

The public has become more aware about the water pollution and its consequences and thus desires strict laws to be made for MCLs (Maximum Contaminant Levels) of different pollutants and their removal. The US Environmental Protection Agency (USEPA) had formulated the Interim Enhanced Surface Water Treatment Rule to prevent the ill-effects of outbreaks of *Cryptosporidium* oocysts and *Giardia* cysts under which it is mandatory to destroy these microbes before release to the environment. For setting the new MCLs for haloacetic acids (HAA) and lowering the MCLs for trihalomethanes (THM), the synthetic organic compounds (SOCs) and nutrients like phosphorous and nitrogen cause a number of harmful impacts on environment and public health, and thus strict regulations need to be made for their discharge.

3.2.3 Industrialization

With the advancements in industrialization, the processes used have become more versatile and costly. Wiesner et al. (1994) used life cycle analysis and found that as compared to the cost of new pressure-driven membrane filtration plants for 20,000 m^3/day, the cost of conventional treatment processes was more.

These problems could be overcome using various advanced technologies that have been proposed, tested and applied for the wastewater treatment. The advanced wastewater treatment technologies have been discussed in detail as follows:

3.3 Advanced Wastewater Treatment Technologies

Some of the advanced wastewater treatment technologies are biological, physico-chemical and hybrid technologies. Biological treatment technologies include biologically enhanced phosphorous removal (BEPR) systems and intermittently decanted extended aeration lagoons (IDEAL) systems for the removal of nitrogen. These do not produce the water to be reused but lays the platform for next treatment processes. Physiochemical processes include membrane filtration and deep bed filtration. Both these methods produce the reusable water and serve the advantages of minimum sludge production and simplicity, respectively. Membrane reactors, the combination of both biological and physiochemical processes, fall under hybrid treatment technologies providing the above said benefits in one single step.

3.3.1 Biological Treatment Technologies

3.3.1.1 Biologically Enhanced Phosphorous Removal (BEPR) Systems

Microbes need phosphorus for their metabolism and an activated sludge contains nearly 1.5–2% phosphorus. The microbes, if grown anaerobically, utilize the polyphosphates from the sludge to consume phosphorus and also generate phosphate store houses for other microbes. In this phosphate can be removed from the sludge if anaerobic conditions are provided in the initial phase and then aerating the sludge. The advantage of this process over chemical processes used for phosphorous removal is that the sludge generated is composed of biological matter which could be disposed of safely. However, this process suffers from the major drawback that it can only be used as a supplementary process to chemical processes and cannot be used alone.

3.3.1.2 Intermittently Decanted Extended Aeration Lagoon (IDEAL) Systems

Domestic waste consists of nitrogen which can be removed by the two-step process. The first step involves the nitrification catalyzed by *Nitrobacter* and *Nitrosomonas* bacteria, in which the ammonia nitrogen is converted to nitrate nitrogen. While in the second step, denitrification takes place, i.e., nitrate nitrogen is converted to nitrate gas. Both the nitrification (aerobic process) and denitrification (anaerobic process) take place in the same tank periodically. The clarified effluent is decanted by lowering the weir of the lagoon. Sewage water is treated using IDEAL systems in Australia for the removal of nitrogen, for example, Quakers Hill STP (Sewage Treatment Plant) in New South Wales.

3.3.1.3 Membrane Bioreactor Technology (MBR)

The separation process in which a semipermeable membrane is used to separate the feed stream into permeate (material passing through the membrane) and retentate (material left behind) is known as membrane filtration (Mallevialle et al. 1996). The combination of activated sludge process and membrane separation process to treat the wastewater is known as membrane bioreactor technology (MBR). In MBR the process is operated in the similar way as activated sludge treatment process without the need of secondary and tertiary treatment steps (sand filtration and clarification). Instead, the effluent is separated from the activated sludge using low-pressure membrane filters such as ultrafiltration (UF) or microfiltration (MF), reverse osmosis (RO) and nanofiltration (NF). Two types of models of MBR are available: sidestream configuration and submerged configuration (Fig. 3.1), but for the treatment of municipal wastewater, submerged configuration is used. Diclofenac, estrone (E1), 17α-ethinylestradiol (EE2), and ibuprofen could be removed using membrane reactors (Kruglova et al. 2016) (Fig. 3.1).

3.3.1.3.1 Submerged Membrane Bioreactor (MBR)

The membranes used in submerged MBRs may be plate membrane design or hollow fiber membrane. The wastewater should be prefiltered with the membrane filter of 3 mm grid distance to prevent the clogging of submerged MBRs. The membrane fouling should be controlled as it would otherwise reduce the flux. The shear forces produced by the turbulence of uprising air and liquid produce a stable flux as it controls the cake layer formation. In submerged MBRs nitrification, denitrification and phosphorous removal can be carried out simultaneously under low sludge loading conditions. Operational parameters could be controlled flexibly with submerged MBRs as it provides sludge retention time (SRT) and hydraulic retention time (HRT). The slow-growing specialized microorganisms are produced when the activated sludge is allowed to remain in contact with the critical class of substrates for a longer period of time. This helps in the removal of low biodegradable pollutants from the wastewater. The trace organic materials discharged from the treated sewage cause a number of pollution and health problems. These include personal care products, pharmaceuticals, and endocrine-disrupting compounds. These compounds can be removed with the help of MBR (Melvin and Leusch 2016).

3.3.1.3.2 Design of MBR

The membrane material used in the reactor greatly influences the success of the MBR. The membrane to be used should be cheap, durable and resistant to chemicals and contaminants and should provide greater permeate flux. The rate with which the permeate passes through the unit area of the membrane is defined as the permeate flux. New membranes have been developed which prove to be efficient for the MBR (Wiesner and Chellam 1999). The inorganic membranes provide resistance to high temperature and chemicals but are expensive and brittle due to which they are not used commercially. Therefore, commercially organic membranes are preferred as they provide higher chemical resistance and water

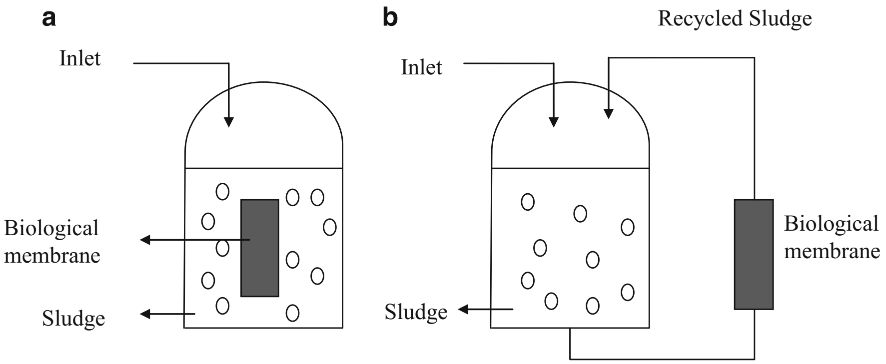

Fig. 3.1 Types of MBR: (**a**) submerged membrane bioreactor; (**b**) sidestream membrane bioreactor

permeability. They are prepared by coating the microporous support with thin layer of active polymer such as polysulfones, polyamides, cellulose acetates and polypropylene. While selecting the membrane, the most important factor that needs to be considered is the molecular weight cutoff (MWC) or the pore size which determines the amount of the solute to be rejected. The membranes are used to separate the microorganisms and particles of about 0.5 μm size under small pressure difference and high flux. RO is used for the desalting of seawater and brackish water as it has the smallest pore size and operates under low permeate flux and high pressure difference. UF and NF are used for the removal of SOCs and natural organic matter (NOM). The applicability of membranes for wastewater treatment has gained much importance as they are available with wide range of pore size and used for the removal of large number of contaminants. The UF and MF consist of hollow fibers which provide high surface area to volume ratio and backwash, but they consume a lot of energy to facilitate high cross-flow velocity. On the other hand, RO and NF have spiral wound configuration which provides reduced concentration polarization/fouling, higher turbulence, and lower deposition of particle cake.

For the reduction of membrane fouling and cost, new designs of MBRs have been proposed and used. A rotating disk membrane filter (Fig. 3.2) was developed by Reed et al. (1997) which consisted of a pressurized membrane with hollow rotating shaft and hollow membrane-covered disks stacked along it. This generates high shear at the membrane surface. The fluid dynamics were studied by Mallubhotla and Belfort (1997), and they developed a special curved model of MBR which reduces the membrane fouling by increasing the vortex at the surface. Another remarkable development of MBR model which helped in the reduction of energy consumption, tolerance to solid loading and high turbidity was the use of hollow submerged fiber bundles. Slight vacuum is applied to the hollow submerged fiber bundles directly mounted in the reactor and permeate is withdrawn.

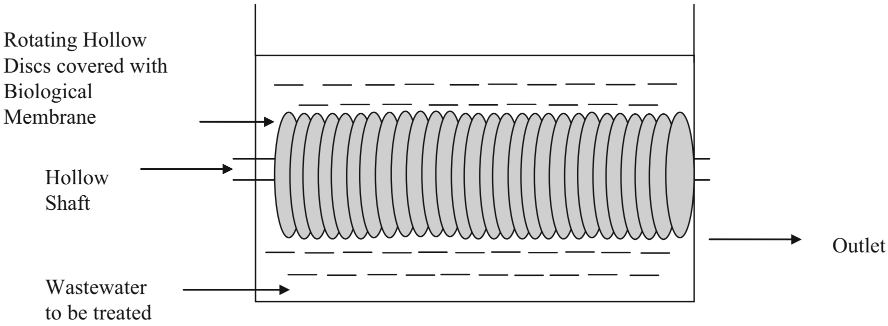

Fig. 3.2 Rotating disk membrane filter

Membrane fouling is reduced by introduction of air from the base which cleans and scours the outer surface of the membrane by creating turbulence.

3.3.1.3.3 Advantages of MBR

MBR serves a number of advantages over the conventional activated sludge treatment process. Some of them are listed below:

1. Higher sludge age due to decreased sludge production.
2. Lower sensitivity to contamination peaks.
3. Due to the use of membrane filters, the effluent is of high quality and more consistent.

3.3.1.3.4 Disadvantages of MBR

Despite the advantages and efficient operation, the MBR has some loopholes such as:

1. Parameters such as temperature, pH and pressure need to be maintained to meet the membrane tolerance.
2. Expensive to install and needs skilled operator.
3. The membrane needs to be frequently monitored and maintained.
4. Some chemicals may damage the membrane.

3.3.1.3.5 Applications of MBR

MBRs serve a number of advantages due to the wide range of pore size available. Out of these the main applications of MBRs are inorganic removal, organic removal and solid-liquid separation.

I. *Inorganic Removal*

The largest application of wastewater treatment is the removal of inorganic compounds by RO and NF. Heavy metals, hardness and nitrates can also be removed by using NF and RO (Waypa et al. 1997). For the small surface water plants with no facilities of groundwater treatment plants, RO has been considered the best technology by USEPA (US Environmental Protection Agency).

II. *Organic Removal*

Dissolved organic compounds such as pesticides from groundwater, dyestuff from textile effluent etc. can be removed from industrial and municipal wastewater by membrane filtration (Brindle and Stephenson 1996; Mallevialle et al. 1996). Other applications of membrane filtration can be in the petroleum industry where the oil is concentrated from oil field brines, treatment of leachate from landfills, product recovery from food processing plants and decolorization of pulp and paper mill effluents. Pretreatment of wastewater with coagulation at pH 5–7 prior to membrane filtration increases the efficiency to remove organic compounds. Pesticides, NOM and DBPs from water with total organic carbon (TOC) concentration greater than 8 mg/L can be removed using RO and NF.

III. *Solid-Liquid Separation*

The solid-liquid separation is usually successful with MF and UF as they can be operated at low-pressure differentials. Chlorine-resistant pathogens (*Cryptosporidium* and *Giardia* species) and turbidity of a wastewater is removed using different types of membrane processes (Yoo et al. 1995; Ventresque et al. 1997). In a comparative study by Jacangelo et al. (1995), it was found that 0.3–0.9 log units of MS2 virus were removed using MF, whereas 6.8 log units of MS2 virus were removed with UF. The efficiency of the MBRs to remove microbial particles and suspended solids can be enhanced by pretreating the samples with coagulation (Wiesner et al. 1989), but excessive coagulation should be prevented as it would cause membrane fouling. This can be overcome if most of the newly formed floc is removed prior to membrane filtration. In addition a disinfectant needs to be added to prevent the regrowth of microbes in the water samples. For the efficient microbial removal of microbial particles, it is necessary to maintain the integrity of the membrane by bubble point testing, sonic sensor, seeded microbial monitoring and air pressure test. One way to maintain the integrity is to use the artificially defective membrane which had a needle hole in it (Adham et al. 1995). It helped in increasing the microbial count in the membrane, but there was no significant effect on the turbidity of the sample.

3.4 Nanotechnology in Wastewater Treatment

Nanotechnology is one of the most finest and advanced ways for the treatment of wastewater. Various reasons behind the success of nanotechnology are that nanoparticles have very high interacting, absorbing and reacting capacities due to their small size with large surface area. They can even be mixed with aqueous suspensions to form colloidal solutions. Energy conservation is achieved by nanoparticles because of their small size. Since water treatment by using nanoparticles has high technology demand, hence its usage cost should be managed according to the existing competition in the market (Crane and Scott 2012). There are various recent advances on different nanomaterials (nanostructured catalytic membranes, nanocatalysts, bioactive nanoparticles, nanosorbents, biomimetic membrane and molecularly imprinted polymers (MIPs)) which have been used for the removal of disease-causing microbes, removal of toxic metal ions and also removal of inorganic and organic solutes from water. Different types of nanomaterials used are listed below:

(a) *Nanocatalysts*

Nanocatalysts have high surface area due to which their catalytic activity is high. Due to this nanocatalysts are used for the treatment of wastewater as it increases the reactivity of contaminants and rate of degradation. Environmental contaminants such as azo dyes, halogenated aliphatics, polychlorinated biphenyls (PCBs), organ chlorine pesticides, halogenated herbicides and nitro aromatics can be degraded by nanocatalysts like semiconductor materials, zero-valence metals and bimetallic nanoparticles (Xin et al. 2011). ZrO_2 nanoparticles, silver (Ag) nanocatalysts and N-doped TiO_2 catalysts are very efficient in degrading microbial contaminants. They have an additional advantage that these nanocatalysts can be reused (Shalini et al. 2012). The TiO_2-AGs are used for the remediation of Cr (IV) in wastewater. The TiO_2 nanoparticles are modified, and due to this their absorption band shifts from UV region to visible region. Thus, TiO_2-AGs are very efficient in removing Cr (IV) from the wastewater. The contaminants like halogenated organic compounds (HOCs) cannot be degraded easily and require advanced nanocatalytic activities. Therefore, the HOCs are first treated with Pd nanocatalysts and then biodegraded in the treatment plant. Depending on the level of contamination, hydrogen or formic acid can be used as reducing agent in the reaction. The nanocatalyst being used possesses ferromagnetism due to which it can be easily separated from the reaction mixture and then reused (Hildebrand et al. 2008). *E. coli* cells could be removed using WO_3 nanocatalysts (Khalil et al. 2009) and palladium-incorporated ZnO nanoparticles (Khalil et al. 2011). Marcells et al. (2009) studied the reduction of Cr (IV) to Cr (II) using palladium nanoparticles (PdNPs). For the combined sorption and degradation of the contaminants, the nanocatalysts could be combined with nanosorbents. Remediation of organic dyes can be achieved by activating the silver and amidoxime fiber nanocatalysts using tetrahydrofuran treatment (Zhi et al. 2010). A mono azo dye, Acid Blue 92 (AB92), could be removed efficiently with Sm (samarium)-doped ZnO nanoparticles (Khataee et al. 2016).

(b) *Nanosorbents*

The nanosorbents for the water treatment processes are mainly being used in Asia and the United States. They have specific and high sorption capacity toward different contaminants. The nanosorbents serve an advantage that they can be removed from the treatment site which reduces the toxicity. Moreover, regenerated nanosorbents are cost-effective and preferred commercially. Ion exchangers, magnetic forces, cleaning agents and many more are used for the removal of nanosorbents from the treatment sites. The specific ligands with specific affinity are coated on the magnetic nanoparticles for the development of magnetic nanoparticles (Apblett et al. 2001). Silver ions can be removed as silver nanocrystals using nanosorbents, poly (aniline-co-5-sulfo-2-anisidine) (Li et al. 2010). Hydrocarbon dyes and phosphorus are removed using nanoclays. The organic contaminants can be removed from the wastewater using magnetic nanosorbents (Campos et al. 2012). Carbon-based nanosorbents have good adsorption capacity, high specific surface area, excellent mechanical strength and chemical resistance. They are used for the treatment of nickel-containing water (Lee et al. 2012). Due to their unique chemical and physical properties, mesoporous silica, chitosan and dendrimers are used as nanosorbents for the removal of heavy metal ions from the contaminated water (Vunain et al. 2016).

(c) *Bioactive Nanoparticles*

Bioactive nanoparticles are chlorine-free biocides which are emerging as a new tool in the treatment of wastewater. MgO nanoparticles and cellulose acetate (CA) fibers with embedded Ag nanoparticles are very effective biocides against gram-positive bacteria, gram-negative bacteria and bacterial spores (Nora and Mamadou 2005). Mesoporous silica nanoparticles could also be used for wastewater treatment processes as they are nontoxic, biologically compatible and easily modified with functional groups (Gunduz et al. 2015). Current and emerging nanotechnology approaches for the detection of microbial pathogens will aid microbial and pathogen detection as well as diagnostics.

(d) *Molecularly Imprinted Polymers (MIPs)*

Molecular imprinting is the process of free radical polymerization to a cross-linker. Molecularly imprinted polymers (MIPs) are one of the finest emerging techniques used in biological, environmental and pharmaceutical applications. They are cheap, simple, robust, selective and nonbiodegradable (Hande et al. 2015; Mattiasson 2015). The specific binding sites are provided to MIPs by the semi-covalent, covalent and non-covalent binding of the functional groups of suitable monomer to the template. Due to this modification, the MIPs are highly selective in nature and also are good absorbents. It is used for the treatment of wastewater and detection of the pollutants even in very low concentration (Caro et al. 2006). The selective nature of the MIPs is a great advantage over other techniques used. Mini-emulsion polymerization technique is used to develop nano-MIPs for the adsorption of micropollutants from hospital wastewater. The particle size of the nano-MIPs is 50–500 nm. For the removal of nano-MIPs from the wastewater after treatment, they could be coated with magnetic core (Tino et al.

2009). The pollution caused during wastewater treatment is treated with MIPs encapsulated in nanofibers using electro-spinning method. A sensor was developed using MIPs for the detection of phosphate levels in wastewater. The developed sensor had a detection limit of 0.16 mg P/L and was simply handheld and did not require filtration of the sample to be monitored like conventional methods such as colorimetry (Warwick et al. 2014). MIPs could be used for the removal of Cd (II), Pb (II), As (V), Hg (II), Ag, Au, Pt, Pd, acitindes, and lanthanides (Hande et al. 2015).

(e) *Nanostructured Catalytic Membranes (NCMs)*

Nanostructured catalytic membranes (NCMs) are preferred due to their optimization capability, limited contact time of catalyst, uniform catalytic sites, easy industrial scale-up and allowed sequential reactions. Membranes under UV-visible light and nanostructured TiO_2 films help in the inactivation of microorganisms, physical separation of water contaminants, anti-biofouling action and decomposition of organic pollutants (Hyeok et al. 2009). The metallic nanoparticles could be immobilized into various membranes such as chitosan, polyvinylidene fluoride (PVDF), cellulose acetate, polysulfone and many more. The immobilized metallic nanoparticles serve a number of advantages such as lack of agglomeration, high reactivity, reduction of surface passivation and organic portioning (Jian et al. 2009). Nanocomposite films have been prepared from polyetherimide and palladium acetate and specific interactions between hydrogen and the Pd-based nanoparticles have been studied proving the efficiency in water treatment. The metal nanoparticles were generated within the matrix by annealing the precursor film under different conditions using both in situ and ex situ method. This provides opportunities to design materials having tunable properties (Clémenson et al. 2010). The N-doped "nutlike" ZnO nanostructured materials showed antibacterial activity, produced clean water with constant high flux and removed water contaminants efficiently by increasing the photodegradation activity (Hongwei et al. 2012).

3.5 Conclusion

Water is an essential requirement for mankind to survive on earth, but with the globalization, the water consumption as well as contamination has increased. Water has been treated using various techniques such as filtration, sedimentation etc., but these techniques cannot generate the water that could be reused by the humans. Therefore, advanced techniques need to be applied to generate water of good quality. Nanosorbents, nanocatalysts, MBRs, NCMs, MIPs and bioactive nanoparticles have been used to treat wastewater. Using these techniques dyes, heavy metals, lanthanides and organic contaminants can be removed from the water and make it fit for human consumption.

Acknowledgment The authors wish to thank Modi Education Society and Dr. Khushwinder Kumar, Principal, Multani Mal Modi College, Patiala for the encouragements.

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