# Perspectives of Bioreactors in Wastewater Treatment

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**Abstract**

Wastewater treatment has become compulsory by government regulations in most parts of the world owing to the importance of maintaining the sanitation of freshwater and preserving the environment. Bioreactors are the core of any biotechnology-based process for enzymatic or microbial biotransformation, bioremediation, and biodegradation. This present chapter summarizes the perspective of the most concerning widespread reactors, such as rotating biological contactor, biological fluidized bed reactor, packed bed reactor, membrane bioreactor, continuous stirred tank bioreactor, upflow anaerobic sludge blanket reactor and photobioreactor, etc., that are most commonly used for treatment of different industrial wastewater. The performance studies of bioreactors carried out by different researchers have also been reviewed.

**Keywords**

Aerobic and anaerobic treatment • Bioreactors • Bioremediation • Municipal wastewater

## 4.1 Introduction

With the escalation in globalization and industrialization, the requirement of clean water in the developing countries has become grievous to attain because of a progressive trend on population, urbanization, and water usage per capita. Enormous quantity of wastewater is generated by residential, commercial, industrial, and institutional establishments. The availability of fresh clean water will become

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severely limited in many areas of the world in the coming years. Water scarcity and water quality are problems facing both developed and undeveloped countries. This encourages many governments on establishing stricter regulations on water resources and water pollution (Copeland and Taylor 2004). For example, excessive usage of water can be reduced by the water-saving campaign and restriction on the use of groundwater. Wastewater standards are also tightened up to protect water resources, such as river, lake, and sea from pollution. These water management regulations made industries do their best efforts on finding a suitable and/or advanced wastewater treatment technology as treated effluent is considered to be environmentally safe and can be used for landscaping purposes or for flushing toilets. Hence, wastewater treatment has become compulsory by government regulations in most parts of the world due to the importance of maintaining the sanitation of freshwater and preserving the environment.

Conventional water and wastewater treatment processes have since long been established in eliminating many physical, chemical, and microbial contaminants of concern to public health and the environment. However, the effectiveness of these processes has become limited over the last two decades because of the new challenges. Firstly, increased knowledge about the consequences from water pollution and, secondly, the public desire for better quality water have promoted the implementation of much stricter regulations by expanding the scope of regulated contaminants and lowering their maximum contaminant levels (Mallevialle et al. 1996). Wastewater is treated through physical, chemical, and biological processes in order to remove contaminants from it so as to generate treated effluent. Some emerging treatment technologies, including membranous filtration, advanced oxidation processes, and the electrochemical method, hold great promises to provide alternatives for better protection of public health and environment. The application of biotechnological processes involving microorganisms, with the objective of solving environmental pollution problems, is gradually growing. Bioremediation processes, which take advantage of microbial degradation of organic compounds, can be defined as the use of microorganisms (especially bacteria) to detoxify and remove environmental pollutants from soils, waters, and sediments.

The bioremediation process, presenting countless advantages in relation to other processes employed, is an evolving method for removal and transformation of many environmental pollutants including those produced by various industries, being one of the most efficient methods to treat polluted environments (Gargouri et al. 2011). Biological treatment using activated sludge in aerobic condition is one of the regularly used treatment methods for industrial effluent. Stabilization ponds, aerated lagoons, or percolating filters are widely applied in aerobic treatment. In aerobic treatment, dissolved oxygen is utilized by microorganism, and, finally, wastes are converted into more biomass and carbon dioxide. Organic matter is partially oxidized, and some of the energy produced is used for generating new living cells under the formation of flocs. Once the flocs are settled down, they are removed as sludge. Bioreactors are the core of any biotechnology-based production processes for vaccine, proteins, enzymatic or microbial biotransformation, bioremediation, and biodegradation (Chishthi and Young 1994). Examples describing above processes, based on immobilized bacteria and fungi, are available at laboratory and industrial scale in fixed-bed reactors (Zhang et al. 1999), trickling filter reactors (where the biofilm is slightly humidified by water or another liquid) (Messner et al. 1990), and rotating biological contactors (where the biofilm develops on the surface of vertical disks that rotate within the liquid) (Kapdan and Kargi 2002). Hollow fiber or membrane biofilm reactors (microbial layer is attached to a porous gas permeable membrane) can provide an efficient gas supply to the base of the biofilm and are considered to be the promising technologies (Lema et al., 2001). Further, the integration of aerobic and anaerobic degradation pathways in a single bioreactor is capable of enhancing the overall degradation efficiency. The integrated bioreactors are classified into four types, which are the following:

- Integrated bioreactors with physical separation of anaerobic–aerobic zone
- Integrated bioreactors without physical separation of anaerobic–aerobic zone
- Anaerobic–aerobic sequencing batch reactors (SBR)
- Combined anaerobic–aerobic culture system

## 4.2 Various Bioreactors Used in Wastewater Treatment

Different types of bioreactors are utilized for the treatment of wastewater that are reliable, cost-efficient, and effective in eliminating a wide range of pollutants. The following sections summarize the potential of different bioreactors such as rotating biological contactor, biological fluidized bed reactor, packed bed reactor, membrane bioreactor, continuous stirred tank bioreactor, upflow anaerobic sludge blanket reactor and photobioreactor, etc., that are most commonly used for treatment of different industrial and domestic wastewater.

### 4.2.1 Rotating Biological Contactor (*RBC*)

Rotating biological contactor is an efficient sewage treatment plant developed on the basis of the original biological filter. It is constituted by a series of closed disks (diameter 1–3 m) made of lightweight materials, such as hard plastic plate, glass plate, etc., that are fixed on a horizontal axis (Fig. 4.1). Nearly half of the disk area is under effluent in the sewage of the oxidation tank, but the upper half is exposed to the air. The rotating horizontal axis is driven by the rotating device that makes the disk rotating slowly. Due to the disk's rotating, the sewage in the oxidation tank is completely mixed. There is a layer of biofilm on the disk surface; when the rotating disk immersed in the sewage inside of the oxidation tank, the organic matter in the sewage would be adsorbed by the biofilm on the disk. When the rotating disk rotates to the air, the water film which is brought up by the disk will drip down along the biofilm surface, and at the same time, the oxygen in the air will dissolve into the water film constantly. Under the catalysis of enzyme, through absorbing the

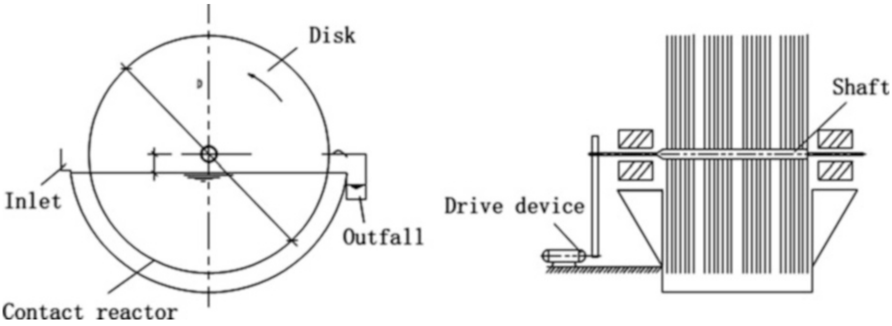


**Fig. 4.1** Diagrammatic scheme of biological rotating contractor

dissolved oxygen in the water film, microorganism can oxidate and decompose the organic matter in the sewage and excrete the metabolite. During disk rotation, the biofilm on the disk gets in touch with the sewage and the air constantly alternating, completing the process of adsorption–oxidation–oxidative decomposition continuously to purify the sewage. The advantages of the biological rotating contactor are power saving, large shock load capability, no sludge return, little sludge generated, little noise, easy maintenance and management, and so on.

The main parameters of affecting the process performance are rotation speed, sewage residence time, reactive tank stage, disk submergence, and temperature. The efficiency of sewage treatment depends upon the consistency sewage, i.e., BOD <300 mg/L; the rotation speed is under 18 m/min. Alternately, at high-BOD consistency sewage, increasing the rotate speed is equivalent to increase the contact, organic loading, hydraulic retention time (HRT), dissolved oxygen, temperature, and submergence (Waskar et al. 2012). Tawfik et al. (2006) investigated the performance of RBC for treatment of domestic wastewater at a temperature of 12–24 °C. The overall nitrification efficiency was 49% at total organic loading rate (OLR) of 11 gm COD/m$^3$/d, and the overall removal efficiencies for chemical oxygen demand significantly decreased when decreasing the total HRT from 10 to 2.5 h and increasing the OLR from 11 to 47 gm COD/m$^3$/d. Moreover, to achieve an effluent quality of BOD (<25 mg/L) and COD (<60 mg/L), the system must have to be operated at organic loadings of about 22 gm BOD/m$^3$/d and 65 gm COD/m$^3$/d, respectively (Ghawi and Kriš 2009).

### 4.2.2 Fluidized Bed Reactor (*FBR*)

A tubular reactor is a vessel through which fluid flow is continuous, generally at steady state, and configured so that conversions of the chemicals and other dependent variables are functions of position within the reactor rather than of time. In the ideal tubular reactor, the fluids flow as if they were solid plugs or pistons, and reaction time is the same for all flowing material at any given tube cross section. Fluidized bed process is also called suspended carrier biofilm process, which is a new efficient sewage treatment process. Figure 4.2 shows the diagrammatic scheme of fluidized bed reactor. The method which adopts the solid particles fluidization technology can keep the whole system at a fluidized state to enhance the contact of solid particles with fluid and achieve the purpose of sewage purification. The growth of microorganism in the fluidized bed reactor was followed by a count of viable cells in both liquid phase and the biofilms attached to the support. An increased number of viable cells were observed inside the reactor when it was used to degrade higher organic loads, with most of the cells on the support. The higher concentration of active biomass was responsible for achieving a relatively high absolute degradation of the wastewater containing the high organic load (Souza et al. 2004). The treatment efficiency is about 10–20 times higher than conventional activated sludge process. It can remove higher organic matter in short time, but the land acreage is only about 5% of the common activated sludge process. Gonzalez et al. (2001) investigated the 90% degradation of phenolic wastewater by the pure culture of immobilized cell of *Pseudomonas putida* ATCC 17484 in fluidized bed bioreactor at a loading rate of 0.5 gm phenol/L/d. Sokół and Woldeyes (2011) evaluated the performance of inverse fluidized bed biological reactor for treating high-strength refinery wastewaters and achieved 96% COD reduction (from 54,840 to 2190 mg/L), when the reactor was operated under optimized operating conditions, i.e., at the ratio (Vb/VR) = 0.55, air velocity u = 0.046 m/s, and time t = 65 h. Haribabu and Sivasubramanian (2016) achieved 97.5% COD reduction at an initial concentration of 2 g/L and for a superficial gas velocity of 0.00212 m/s at HRT of 40 h using fluidized bed reactor containing biocarrier made up of low-density (870 kg/$m^3$) polypropylene of surface area 524 $mm^2$ per particle. Further, anaerobic treatment of textile wastewater was possible with the supplementation of substrate additives as external carbon sources such as 0.6 gm/L of glucose (Haroun and Idris, 2008) and 2.0 gm/L of glucose (Sen and Demirer 2003), and a further increase in the external carbon source added to textile wastewater did not improve the color removal efficiency of the anaerobic FBR reactor. The study implied that 98% soluble COD, 95% $BOD_5$, and 65% color reduction were possible by an anaerobic FBR for HRT of around 24 h and OLR of 3 kg COD/$m^3$/d. Aerobic digestion of starch industry wastewater was carried out in an inverse fluidized bed bioreactor using low-density (870 kg/$m^3$) polypropylene particles (Rajasimman and Karthikeyan 2007). Constant biomass loading was achieved over the entire period of operation, and maximum COD removal of 95.6% occurs at an OLR of 1.35 kg COD/$m^3$/d and a minimum of 51.8% at an OLR of 26.73 kg COD/$m^3$/d.

### 4.2.3 Packed Bed Reactor (*PBR*)

These reactors are tubular and filled with microbial biomass/pellets, and the biochemical reaction takes place on the surface of the microbial biomass. A fixed-bed reactor usually consists of a cylindrical vessel packed with microbial pellets that are easy to design and operate. The metal support grid and screen is placed near the

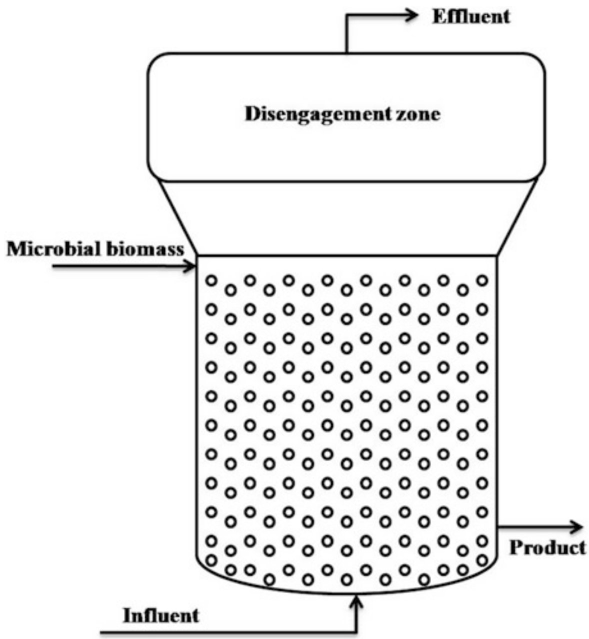


**Fig. 4.2** Diagrammatic schematic of fluidized bed reactor

bottom to support the microbial pellets. Inert ceramic balls are placed above the microbial biomass bed to distribute the feed evenly (Fig. 4.3).

An anaerobic packed bed reactor was employed to treat highly polluted pharmaceutical wastewater having high COD (80,000 mg/L) (Chelliapan et al. 2011). Seventy-three percent COD reduction was attained at an average reactor OLR of 1.58 kg COD/m$^3$/d (HRT 5.6 d). Further, with the increase in OLR from 2.21 to 4.66 kg COD/m$^3$/d, the COD removal efficiency decreased gradually up to 60–70%. The average COD and SS removal efficiencies for domestic wastewater were 75.92% and 94.25%, respectively, in an upflow anaerobic packed bed reactor (Bhuyar 2013). On changing pH from 7.2 to 4.2, biogas was produced 0.50–0.59 L/d on same HRT. The performance of an anaerobic fixed bed reactor installed at a chemical industry producing organic peroxides was investigated for sulfate removal from sulfate-rich wastewater (sulfate concentrations ranging from 12,000 to 35,000 mg $SO_4^{2-}$/L) (Silva et al. 2002). A maximum sulfate removal efficiency of 97% was reached during discontinuous and semicontinuous operations. Further, Abdullah et al. (2016) achieved the removal of 98% COD and 93% TOC during the treatment of high-strength organic brewery wastewater with added acetaminophen (AAP) with an anaerobic packed bed reactor (APBR) operated with an organic loading rate of 1.5gm COD/L and 3 days HRT. The average $CH_4$ production decreased from 81 to 72% is counterbalanced by the increased $CO_2$ production from 11 to 20% before and after the injection of AAP, respectively. Similarly, the hydrogen sulfide ($H_2S$) removal by sulfur-oxidizing bacteria isolated from the sludge of the wastewater of a biogas plant, attached as a

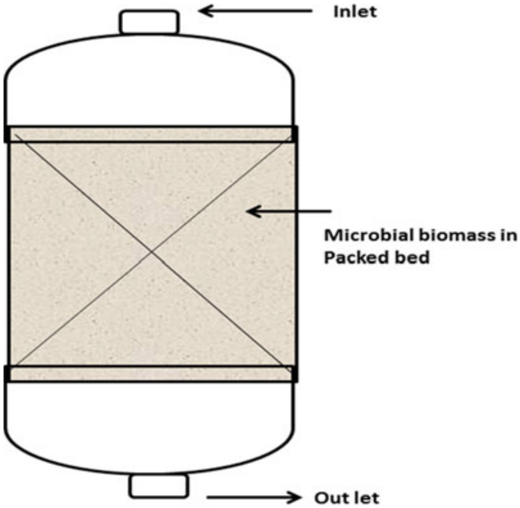


**Fig. 4.3** Diagrammatic scheme of packed bed reactor

biofilm on salak fruit seeds, was studied with packed bed reactor by Lestari et al. (2016), and they observed the decrease in $H_2S$ in biogas from 142.48 mg/L to 4.06 mg/L (97.15% removal efficiency) for a biogas flow rate of 8550 gm/m$^3$/h corresponding to a residence time of 4 h.

### 4.2.4 Membrane Bioreactor (*MBR*)

These are widely used nowadays for municipal and industrial wastewater treatment. These are suspended growth bioreactors which are integrated with a membrane process like microfiltration or ultrafiltration and are involved in treatment processes, which make use of a semipermeable membrane with a biological process. A membrane is simply a two-dimensional material used to separate components in the fluids on the basis of their relative size or electrical charge. The semipermeable membrane allows only specific components to pass through them without changing their properties. The filtrate part is known as permeate, while residual retained on membrane is called as concentrate or retentate. The typical diagrammatic sketch of membrane bioreactor has been in Fig. 4.4. Different types of membrane configuration that are currently in operation are hollow fiber, spiral wound, plate and frame, pleated filter cartridge, tubular type, etc. The advantages of MR technology are (a) secondary clarifiers and tertiary filtration processes are eliminated, thereby reducing plant footprint; (b) can be designed to prolong sludge age, hence lower sludge production; (c) high effluent quality; and (d) high loading rate capability.

The municipal wastewater was treated with submerged membrane bioreactor technology (Zhidong et al. 2009) and observed the average removal rate of COD and BOD over 90% in addition to the 99% removal rate of $NH_3$–N. Moreover, Sima et al. (2011) revealed the effect of virus removal from the wastewater samples using

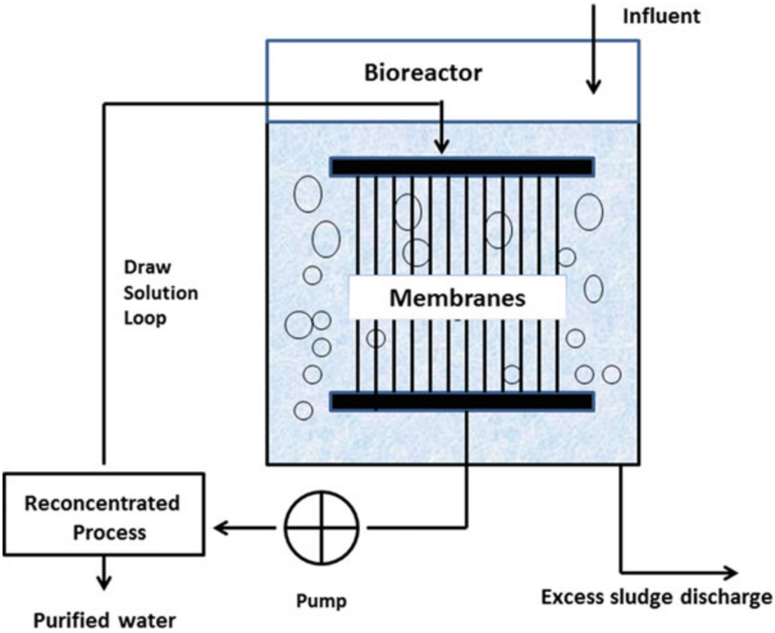


**Fig. 4.4** Diagrammatic sketch of membrane bioreactor

membrane bioreactor wastewater treatment in southwest France and analyzed the calicivirus (*Norovirus* and *Sapovirus*), adenovirus, and *Escherichia coli*. The results demonstrated that the viruses were blocked by the membrane in the treatment plant and were removed from the plant as solid sludge. *E. coli* was found to be below the limit of detection in the effluent. Overall, the removal of calicivirus varied from 3.3 to greater than 6.8 log units, with no difference between the two main genogroups. Further, low-strength wastewater (Martinez-Sosa et al., 2011) and high-strength wastewater (Jager et al. 2013) were treated with an anaerobic submerged membrane bioreactor. The membrane area is determined by the hydraulic throughput and not the biological load; no sludge is wasted, and all bacteria are retained within the reactor, including specific bacteria capable of degrading the toxic, nonbiodegradable constituents present in textile wastewater. Besides biogas sparging, additional shear was created by circulating sludge to control membrane fouling. 75–97% reduction of COD was achieved over the 220-day test period, which was well within permissible limits of wastewater discharge standard. An average 91% conductivity rejection was achieved with conductivity being reduced from an average of 7700 to 693 μS/cm and the TDS reduced from an average of 5700 to 473 mg/L, which facilitated an average TDS rejection of 92% (Jager et al., 2013). Boonyungyuen and Wichitsathian (2014) studied the removal efficiencies of HMBR which were higher than MBR system, and the TKN removal of hybrid membrane bioreactor (HMBR) system is higher than MBR at 14.2% operated at HRT of 24 h under anaerobic digestion, which is due to the biofilm on activated carbon surface that allows anoxic condition inside porous biofilm and enhances nitrite/nitrate removal efficiency. Membrane reactor is a promising technology for wastewater treatment and water reclamation, but even then it has certain disadvantages such as high operation and capital costs of membranes, membrane complexity and fouling, energy costs, etc.

### 4.2.5 Continuous Stirred Tank Bioreactor (*CSTR*)

The continuous stirred tank bioreactor (CSTR) is the idealized opposite of the well-stirred batch and tubular plug flow reactors. In the CSTR, the reactants and products are continuously added and withdrawn. In practice, mechanical or hydraulic agitation is required to achieve uniform composition and temperature, a choice strongly influenced by process considerations. Compared to other configurations, the CSTR provides greater uniformity of system parameters, such as temperature, mixing, chemical concentration, and substrate concentration. The CSTR is frequently used in research due to its simplicity in design and operation, but also for its advantages in experimentation. The primary design and operational target of the ASP for BOD removal is obtaining good solids settling properties in secondary clarifier. For instance, food to microorganisms (F/M) ratio is limited at 0.2–0.4 g BOD/gm MLSS/d in a typical ASP to obtain biosolids with a good sludge settling properties, although microorganisms can accommodate much higher F/M ratio. Usack et al. (2012) studied the use of continuously stirred anaerobic digester to convert organic wastes into biogas (Fig. 4.5).

The continuously stirred tank bioreactor was used to optimize feasible and reliable bioprocess system for the removal of dye (sulfur black) from textile effluent (Andleeb et al. 2010) as well as to treat hydrocarbon-rich industrial wastewater (Gargouri et al. 2011). In former case, the *Aspergillus terreus* SA3 isolated from the textile contaminated sites was used, and overall color, BOD, and COD in the continuous stirred tank bioreactor (CSTR) system were removed by 84.53, 66.50, and 75.24%, respectively, with 50 mg/L dye concentration and HRT of 24 h. The removal efficiency of the reactor decreased as the concentration of the dye was increased. This CSTR system was found very effective for efficient treatment of textile wastewater (up to 200 mg/L sulfur black dye) by the fungal strain *A. terreus* SA3, whereas in the latter case, an efficient acclimatized microbial consortium was used for decontaminating the hydrocarbon-rich wastewater. The performance of the bioaugmented reactor was demonstrated by the reduction of COD rates up to 95%. The residual total petroleum hydrocarbon (TPH) decreased from 320 to 8 mg TPH/L. It was further observed that, during the treatment process, the degradation of hydrocarbons was enhanced, implying that the aerobic treatment is an effective bioremediation technology. These encouraging results are mainly due to the development of an efficient microbial consortium and to the optimization of specific hydrodynamic conditions of the bioreactor.

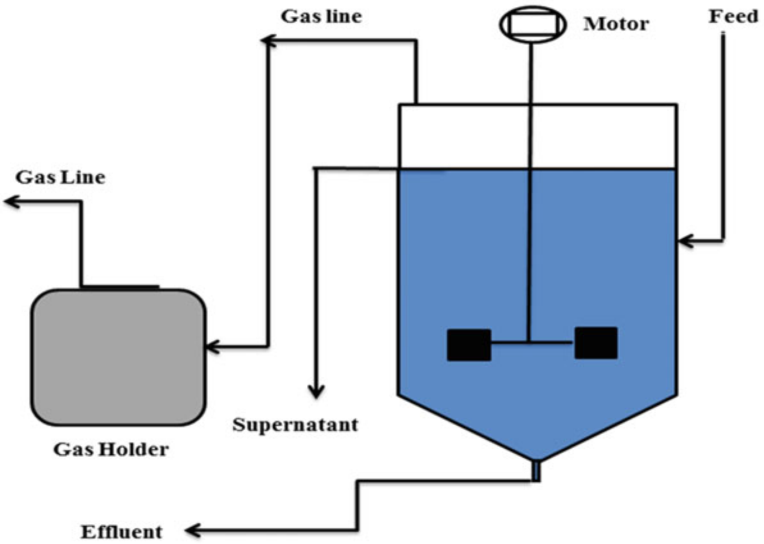


**Fig. 4.5** Diagrammatic scheme of continuous stirred tank bioreactor (CSTR)

### 4.2.6 Upflow Anaerobic Sludge Blanket (*UASB*) Reactor

Upflow anaerobic sludge blanket technology, normally referred to as UASB reactor, is a form of anaerobic digester that is used for treatment of industrial wastewater. The UASB reactor is a methanogenic (methane-producing) digester that evolves from the anaerobic clarigester. The UASB reactor uses an anaerobic process while forming a blanket of granular sludge which suspends in the tank. The UASB is widely applicable for treating various types of wastewater and has advantages over aerobic treatment. Wastewater flows upward through the blanket and is processed (degraded) by the anaerobic microorganisms. The upward flow, combined with the settling action of gravity, suspends the blanket with the aid of flocculants (Fig. 4.6). Tiny sludge granules begin to form whose surface area is covered by aggregations of bacteria. In the absence of any support matrix, the flow conditions create a selective environment in which only those microorganisms capable of attaching to each other survive and proliferate. Eventually, the aggregates formed into dense compact biofilms are referred to as "granules." Bacteria living in the sludge break down organic matter by anaerobic digestion and transform into biogas. Solids are also retained by a filtration effect of the blanket. Baffles at the top of the reactor allow gases to escape and prevent an outflow of the sludge blanket.

Like aerobic treatments, the UASB requires a posttreatment to remove pathogens, but due to low removal of nutrients, the wastewater, as well as the stabilized sludge, can be used in agriculture. Three different types of upflow anaerobic reactor such as upflow anaerobic sludge blanket (UASB), upflow

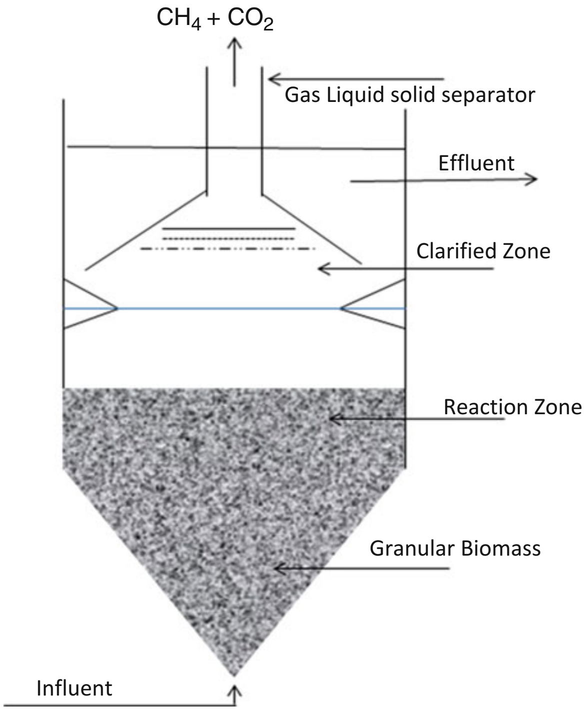


**Fig. 4.6** Diagrammatic sketch of upflow anaerobic sludge blanket (UASB) reactor

anaerobic sludge-fixed film (UASFF), and upflow fixed film (UFF) reactors are used in the anaerobic process. In this anaerobic treatment, complex organic matter is converted into methane gas through the stages like hydrolysis, acidogenesis, and methanogenesis. Anaerobic hybrid reactor is a combination of upflow anaerobic sludge blanket (UASB) and upflow fixed film (UFF) reactors. The lower part of the UASFF reactor is the UASB portion where flocculants and granular sludges are developed. The upper part of the UASFF reactor serves as a fixed film bioreactor. The UASFF reactor has been used successfully for the treatment of various industrial wastewaters.

Researchers have used an upflow anaerobic sludge-fixed film (UASFF) reactor also termed as granular sludge bioreactor for the biological conversion of organic matter to biogas with the aids of aggregated microbial consortium in order to shorten the start-up period up to 4–5 days at 36 °C and HRT of 36 h. The organic loading rate was gradually increased from 7.9 to 45.42 gm COD/L/d. Further, a hybrid upflow anaerobic sludge blanket (HUASB) reactor was used for the treatment of domestic wastewater (Banu et al. 2007). The COD and BOD removal varied in the range of 75–86% and 70–91%, respectively. Methane content in the biogas was 62 ± 3%. VFA levels fluctuating between 100 and 186 mg/L and nutrient levels exhibited an increasing trend. The HUASB system could be designed with very short HRT of 3.3 h, which will reduce the treatment cost significantly. It appears to be a promising alternative for the treatment of domestic wastewater in developing countries, like India. The anaerobic treatment of presettled cosmetic wastewater was studied in batch and continuous UASB reactor by Puyol et al. (2011). High COD and TSS removal efficiencies (up to 95% and 85%, respectively) were achieved over a wide range of organic load rate (from 1.8 to 9.2 gm total COD/L/day) in continuous treatment in an UASB reactor. Ferraz et al. (2011) evaluated the treatment of effluent from a jean factory using an upflow anaerobic sludge bed (UASB)-submerged aerated biofilter (SAB) system in different three phases, each with a different hydraulic retention time (HRT in hr) and organic loading rate (OLR in kg COD/$m^3$/d) up to 210-day operational period. In the first phase, best performance was achieved using the UASB (HRT 24 h, OLR 1.3) with COD and color removal efficiencies of 59 and 64%, respectively; the corresponding values were 77 and 86% for the final effluent. The use of a sequential anaerobic–aerobic system is promising for treatment of textile industrial wastewater.

## 4.3 Photobioreactor

A photobioreactor is a bioreactor that utilizes a light source to cultivate phototrophic microorganisms. These organisms use photosynthesis to generate biomass from light and carbon dioxide and include plants, mosses, macroalgae, microalgae, cyanobacteria, and purple bacteria. Algae have attracted much interest for production of foods, for bioactive compounds, and also for their usefulness in cleaning the environment (Fig. 4.7).

Kwangyong and Lee (2002) studied the microalgal nitrogen treatment with *Chlorella kessleri* in artificial wastewater with a low carbon/nitrogen (C/N) ratio with nitrate and glucose as a nitrogen and carbon source, respectively, along with abiotic control. The growth rates of the two cultures were almost identical when the aeration rate was over 1 rpm, and further, microalgae could successfully remove nitrogen from wastewater. Nitrate was successfully reduced to below 2 mg $NO_3$-N/ml from the initial nitrate concentration of 140 mg $NO_3$-N/ml in 10 days, even in the wastewater with no organic carbon source. However, the treatment of domestic wastewater with treatment (aerated and nonaerated) with *Chlorella vulgaris* under semi-controlled conditions in semi-closed photobioreactors in a greenhouse was performed (Marchello et al. 2015). Insignificant variations in pH and coliforms were observed between treatments. Nutrient concentrations were decreased supporting microalgae growth up to 107 cells/mL independent of aeration. Effluent is viable for the microalgae growth of *Chlorella vulgaris*, and at the same time the eutrophication potential decreased, contributing for better quality of the final wastewater. *Chlorella sorokiniana* isolated from White Sea, a suitable feedstock for biodiesel production was cultivated in semi-batch mode in a high-density photobioreactor for the bioremediation of alcohol distillery wastewater (Solovchenko et al., 2014). A decrease in COD from 20,000 to 1500 mg/L was achieved over 4 days with a decline in 95% nitrate, 77% phosphate, and 35% sulfate at pH 6.0–7.0. Another hollow fiber membrane photobioreactor (HFMPB)

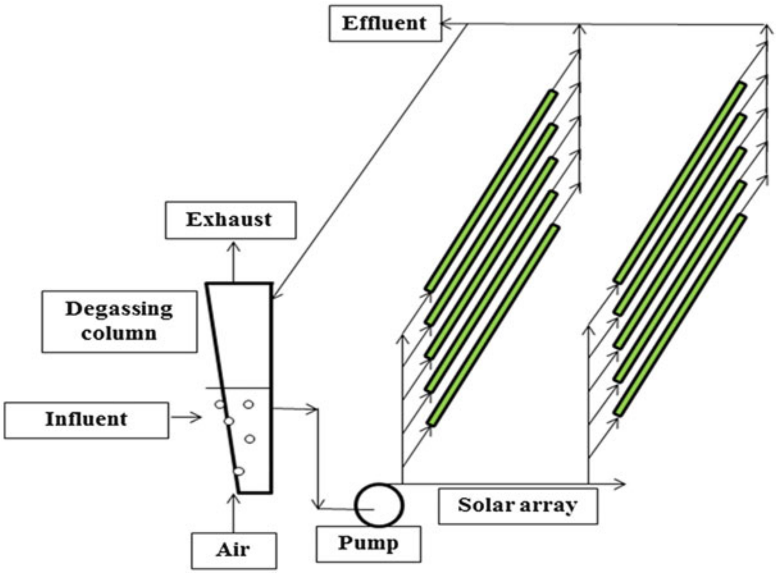


**Fig. 4.7** Diagrammatic sketch of photobioreactor

containing *Spirulina platensis* used for biofuel production was operated with a 2–15% $CO_2$ supply (Kumar et al., 2010). The algal biomass concentrations and $NO_3$ removal efficiencies were 2131 mg/L and 68%, respectively. The combination of $CO_2$ sequestration, wastewater treatment, and biofuel production using *Spirulina platensis* in an HFMPB was found to be a promising alternative for greenhouse gas mitigation. Christenson and Sims (2011) reported the integration of microalgae-based biofuel and bioproducts production with wastewater treatment has major advantages for both industries. However, major challenges to the implementation of an integrated system include the large-scale production of algae and the harvesting of microalgae in a way that allows for downstream processing to produce biofuels and other valuable bioproducts. Although the majority of algal production systems use suspended cultures in either open ponds or closed reactors, the use of attached cultures may offer several advantages. With regard to harvesting methods, better understanding and control of autoflocculation and bioflocculation could improve performance and reduce chemical addition requirements for conventional mechanical methods that include centrifugation, tangential filtration, gravity sedimentation, and dissolved air flotation. There are many approaches currently used by companies and industries using clean water at laboratory, bench, and/or pilot scale; however, large-scale systems for controlled algae production and/or harvesting for wastewater treatment and subsequent processing for bioproducts are lacking. Further investigation and development of large-scale production and harvesting methods for biofuels and bioproducts are necessary, particularly with less studied one, but the promising approaches such as those involving attached algal biofilm cultures.

## 4.4 Conclusion

A number of significant trends are used in wastewater treatment, and they influence the near- and long-term alteration at wastewater treatment facilities. Undoubtedly bioreactor technology is advancing rapidly around the globe for municipal and/or industrial wastewater treatment both in research and commercial applications. Literary survey established that bioreactors are the core of biotechnological processes such as microbial transformation, bioremediation, and biodegradation which may hold the utmost promising alternative for efficient treatment of wastewater of a variety of strengths and compositions producing a pathogen-free treated water of excellent quality in addition to production of good quality fuel (biogas), a renewable energy. In spite of this, the adoption and commercialization of this technology at industrial scale is still in low pace.

The usage of bioreactors either independently or in combination as hybrids hold great promises in future, as they provide most effective and economical approach to deal with challenging environmental problems. Moreover, advance research is desirable for better understanding both synergistic and adverse effects, and further experiments are still needed to develop and evaluate the performance of hybrid bioreactors to clean the industrial effluent at low cost so that resultant could be recycled in the process to meet both current and anticipated treatment requirements. Nowadays, MBRs are widely used for aerobic wastewater treatment, as they are capable of producing a high-quality effluent with low-suspended solid concentration and small footprint relative to traditional aerobic treatment systems, but use higher energy to reduce membrane fouling. Researchers are focusing on new MBR design, the anaerobic fluidized membrane bioreactor, which combines a membrane system with an anaerobic fluidized bed reactor which will be more energy efficient and cost-effective.

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