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Microbial Bioremediation and Different Bioreactors Designs Applied

Memory Tekere

Abstract

Microbial remediation of pollutants involves the use of microorganisms to degrade pollutants either completely to water and carbon dioxide (for organic pollutants) or into less toxic forms. In the case of nonbiodegradable inorganic compounds, bioremediation takes the form of bioaccumulation or conversion of one toxic species to a less toxic form for example Cr(VI) is converted to less toxic (III). Bioremediation is considered an environmentally friendly way for pollution clean-up. Microbial clean up can be applied *in situ* (in place of contamination) or *ex situ* (off the site of contamination). *In situ* remediation in the natural environment is deemed slow and often times difficult to control and optimize the different parameters affecting the bioremediation. To this end, use of engineered bioreactors is preferred. Engineered bioreactors providing for optimum conditions for microbial growth and biodegradation have been developed for use in bioremediation processes to achieve the different desired remediation goals. Bioreactors in use range in mode of operation from batch, continuous, and fed batch bioreactors and are designed to optimize microbial processes in relationship to contaminated media and nature of pollutant. Designed bioreactors for bioremediation range from packed, stirred tanks, airlift, slurry phase, and partitioning phase reactors amongst others.

Keywords: bioremediation, bioreactors, pollution, microorganisms, degradation

1. Introduction

Bioremediation is a natural process that relies on microorganisms and plants and/or their derivatives (enzymes or spent biomass) to degrade or alter environmental contaminants as these organisms carry out their normal life functions [1, 2]. Bioremediation is considered an economical, versatile, efficient and eco-friendly way of dealing with environmental pollutants as compared to the physico-chemical methods [1–3]. The use of well-designed microbial bioreactors is acknowledged as an efficient way to ensure that microbial growth and processes occur in a controlled environment that provides the necessary optimum conditions [3–5]. This chapter focuses on microbial remediation in bioreactors so phytoremediation as facilitated by plants is not discussed. Several studies describe microbial remediation in designed bioreactors ranging from batch, continuous, and fed-batch operated mode which can be in different designs such as suspended carrier, slurry and fixed bed, membrane and fluidized bed reactors [4–8].

The use of microbial bioreactors in remediation is very attractive in that the bioreactors offer the advantages of providing a controlled environment where it is possible to control critical process parameters to optimize the microbial bioremediation process. Another advantage is that there is flexibility in design of the bioreactor (size and configuration) to suit application or intended purpose of the reactor [6–9]. However, bioremediation in bioreactors if operated *ex situ*, requires relocation of pollutant, a process which can involve excavation for soils and sediments, transportation and possible containment or controlled handling of the contaminated media thus making the process expensive [4–6, 8, 9]. There is a potential for exposing other environments to the contamination. Also some pretreatment of contaminated media, e.g., drying and crushing, maybe required thus adding on to the process cost [8, 9].

2. Microbial bioremediation

As defined, microbial bioremediation makes use of microorganisms and/or their derivatives (enzymes or spent biomass) to clean-up environmental contaminants [7, 9, 10]. With microorganisms, it is important to note that microorganisms are everywhere and as such pollutants in the different environmental compartments always come into contact with microorganisms [1, 2]. Microbes break down/transform pollutants via their inherent metabolic processes with or without slight pathway modifications to allow the pollutant to be channeled into the normal microbial metabolic pathway for degradation/and biotransformation. Applied bioremediation methods therefore focus on tapping the naturally occurring microbial catabolic capabilities to degrade, transform or accumulate most of the synthetic compounds such as hydrocarbons (e.g., oil), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), radionuclides and metals [4, 6–8]. The natural existence of a large diversity of microbial species expands the variety of chemical pollutants that are degraded or detoxified.

The advantages of microbial bioremediation are that it has public acceptance, as it is a natural process [8]. It is a low cost technology in most cases when compared to other clean-up methods for hazardous waste [2]. It can be done *in situ* and *ex situ*, instead of contaminants being transferred from one form to another or one medium to another, complete destruction of target organic pollutants is possible [8]. Notable disadvantages are that bioremediation takes relatively long to achieve treatment goals, may not be effective on all contaminants, some products of biodegradation maybe more toxic or persistent than the parent compound, specificity of the biological processes with respect to microbial populations, pollutant and environmental limitations is also a drawback and that specialized expertise are required in designing and implementing.

Bioremediation using microbial bioreactors finds application in soil, air and water environments including:

- Waste water and industrial effluent treatment

Microorganisms are the primary agents of any biological wastewater treatment. Microorganisms are already present in waste water systems and feed on complex substances in the wastewater converting them to simpler substances thus assisting in achieving the treatment. Trickling filters, membrane bioreactors, slurry phase reactors and upflow anaerobic sludge blanket bioreactors (UASB) are some of the reactors that are used in waste water and industrial effluent treatment.

- Soil and land treatment

Contaminants successfully treated include diesel fuel, fuel oils, oily sludge, wood-preserving wastes (PCP, PAHs, and creosote), coke wastes, and certain pesticides [6, 8, 9]. Soil bioremediation has proven most successful in treating petroleum hydrocarbons and other less volatile, biodegradable contaminants. Slurry phase, stirred tanks, biofilters, partitioning phase and packed microbial reactors find application in contaminated soil remediation.

- Control of air pollution

Microorganisms are used in the bioremediation of organic and inorganic air pollutants in spent gases before release or escape into the atmosphere [5, 9]. Microorganisms oxidize pollutants such as H₂S, SO₂, VOCs, and reduce pollutants such as NO_x to nitrate and this assist to prevent likely environmental, health hazards and nuisances [5]. Bioscrubbers and biofilters are some of the bioreactor types often used in control of air pollution.

- Solid waste management

Microorganisms are chiefly responsible for the biodegradation of organic wastes in nature and they drive the decomposition processes that occur in landfills and composts. Anaerobic digesters are often applied mostly in the biotreatment solid waste.

2.1 Factors affecting microbial bioreactor performance

A number of issues are at play in all bioremediation technologies including when bioreactors are used. These are those that concern the contaminant, microbial community and the design, optimization and monitoring of the process [6, 8, 9]. The microbial science of bioremediation is therefore approached from many scientific frontiers: abiotic interactions (solubility, transport, sorption and photolysis), biotic interactions (taxonomic diversity, physiological, genetic and ecological interactions). In the design and operation of bioreactors in remediation, many of these factors have to be optimized and controlled for best reactor performance [5, 10–12].

Variables that affect the operation and efficiency of a microbial bioreactor relate to biotic and abiotic factors that affect microbial growth and those factors that relate to the reactor design and configuration. Factors that affect microbial growth and activities in bioreactors include; environmental factors (temperature, pH, moisture), pollutant mix, pollutant concentration, macronutrient [5, 10–12]. Factors on reactor design include; size, configuration and mode of operation.

- Environmental related factors

Environmental conditions (temperature, pH, oxygen availability/electron, and salinity) affect growth; the metabolic activities of microorganisms and to some extent the behavior of the pollutant such as solubility and volatility [11]. In any process optimization for biodegradation, it is always necessary to investigate the effects of the environmental conditions and optimize the process in relationship to all the relevant environmental conditions. Tekere et al. [13], established the optimum growth conditions with respect to pH, aeration and nutrients in the growth and degradation of pollutants by white rot fungi and found that optimized conditions result in high enzyme and degradation activities.

- Temperature

There is always a temperature range at which microorganisms grow and survive (i.e., minimum, optimum and maximum survival temperature). In addition, there is always a temperature optimum at which biochemical processes take place to achieve required bio treatment by each microorganism [13]. Extremes of temperature (too low or too high) affect both microbial growth and microbial enzyme catalyzed reactions [2]. With an increase in temperature within appropriate range, microbial metabolism increases and thus the rate of the bioremediation processes.

Increased temperatures lead to higher solubility of many chemicals, and increased fluidity and diffusion rates. For example with pollutants, such as PAHs and heavy metals, their solubility and in turn bioavailability increases with temperature [2, 7]. Temperature is thus a critical factor in the optimum operating efficiency of bioreactors to achieve best biotreatment results. Often specialized bioreactors are designed with provision for temperature control.

- pH

Similar to temperature, pH affects microbial growth and metabolic processes. pH influences microbial cell ionic properties thus microbial growth. Microorganisms have minimum, optimum and maximum pH of growth with most bacteria for example growing optimally at pH 6–7.5, though there are some which thrive best at acidic pHs (acidophiles) or at alkaline pH (alkaliphiles). Fungi generally grow at pHs lower than that of bacteria. Reactor operating pH has to be set to provide the best pH conditions for growth and enzyme activities. Behavior of pollutants is also influenced by pH thus affecting their bioremediation. For example with metals, pH affects the redox and solubility of metals, different forms and valence have different effects on microorganisms [14]. Metal solubility increases with a decrease in medium pH and alkaline pH favor metal ion precipitation. Often lower pH values are required for metal attachment to the microbial cell surface [7, 14]. Microorganisms that produce acids result in increased solubility of the metal ions [10]. To provide for best pH conditions, buffers are used in media formulations, acids and bases can be added during the bioreactor process [13].

- Nutrients

Nutrients are required for growth and metabolism of the microorganisms. Several elements are required in biosynthesis and energy production. Carbon is the most basic element of living forms and is needed in greater quantities than other elements. Other elements that are important in ensuring a balanced nutritional bioreactor environment depending on the type of microorganism include hydrogen, oxygen, nitrogen, sulfur, phosphorus, iron, calcium and magnesium [10, 11]. All necessary macro- and micro- nutrients requirements are provided in reactor media. Microorganisms can use the pollutants they are degrading as primary energy sources or a primary source of energy is provided to the microorganism in the case of co metabolism of the pollutants.

- Moisture

Water is required to support microbial growth and catalysis. Cellular chemical reactions occur in aqueous conditions and water is required to ensure the correct osmotic pressure is maintained for microbial growth. The amount of water available

for microbial growth is called (aW). Most microorganisms grow at water activities of 0.98 or higher, osmotolerant species can however grow at a range of low aW [11].

- Electron acceptors

The presence of electron acceptors, e.g., oxygen in aerobic microbes and NO_3^{1-} , SO_4^{2-} and Fe (III) oxides in case of anaerobic microbes, also affects the biodegradation processes.

- Reactor design related factors

Bioreactors have to provide for the best conditions for microbial growth and biochemical process to occur. The reactor size, configuration and mode of operation are key reactor design factors. The reactor should provide favorable physical, biological and the combined physical-chemical conditions for the best biological remediation processes to be achieved. In designing the bioreactor, favorable physical conditions for transport of gases and liquids and solids over time that ensure that the physical entity of the bioreactor is favorably adapted to the biological system that performs the bioreactions are required [12, 15]. On the other hand there is need to ensure that the biophysical and biochemical events taking operate at optimum levels under real situation application.

Polluted samples for remediation can be fed into the reactor either as dry or slurry matter [9]. Pollutants with hydrophobic properties are often unavailable for microbial degradation, particularly if they are bound to soil matrix [7]. Their degradation is therefore limited by their transfer to liquid [4]. Minimizing mass transfer resistance was found to be a key factor in the degradation of hexachlorocyclohexane (HCH) in slurry batch bioreactors [4].

Despite the rapid development of bioreactors due to their widespread use in biotechnology, the aspects of maintaining stability and rates of bioprocesses are still areas to be addressed. Poor bioreactor construction and design, leading to inadequate mixing, may jeopardize the stability and performance of the process [15]. Mixing prevents thermal stratification, help maintain uniform conditions in the reactor, ensure good contact between microbial culture and media reactants. The importance of mixing in bioreactor cannot be over emphasized, poor mixing affect microbial process efficiency.

Hydraulic retention times (HRT) required to achieve the necessary remediation goals in the bioreactor have to be determined and optimized. Longer HRTs result in poor substrate loading which diminishes the microbial population, whereas shorter ones do not allow microorganisms to effectively degrade the pollutant and can result in microbial wash out from the system [16].

- Organism related factors

Organism related factors include population density, composition, inter and intraspecific interaction. Microbes are the most diverse forms of life and have developed a wide range of metabolic pathways that enable them to cope under the varying ecological conditions including exposure to xenobiotics. A whole range of environments ranging from aerobic, anaerobic, acidic, alkaline, and low to high temperature have been utilized as sources of microorganisms for bioremediation [13]. Only certain species of bacteria and fungi have proven their ability as potent pollutant degraders [13]. In the natural environment degradation of pollutants is often achieved through complex microbial population interactions. Single or mixed microbial cultures are used for pollutant remediation in bioreactors. In the event

where bioaugmentation is applied the introduced organisms need to be able to co-exist with indigenous residents.

Different microorganisms often have different metabolic capabilities, to this extend the evaluation of several strains of different microbial players have to be investigated in order to come up with the best degraders [13]. In screening and comparison of the bio-degradation of PAHs by white rot fungi [17], found out that newly screened white rot fungi strains had higher or comparable degradation capacity to the model well applauded *P. chrysosporium*, and these strains did not accumulate the metabolite quinone which accumulates as a dead end metabolite in *P. chrysosporium*.

Polluted environments provide sources of microorganisms resistant or acclimated to the pollutant [18]. However microorganisms that are known to have certain inherent physiological characteristic, e.g., metabolism of known substrate with structural similarity to xenobiotics of interest and/or adaptation to certain environmental conditions can be selected. This is the case in several studies that used microorganisms for pollutant degradation [11, 17–19].

- Pollutant related factors

Factors that affect bioremediation in bioreactors that are related to the pollutant include: nature of pollutant, i.e., the physical and chemical properties including solubility, volatility, molecular complexity, concentration and toxicity. Investigations for most pollutant biodegradation have centered on how different concentrations, mixed pollutants, solubility and molecular structure can affect microbial bioremediation [17, 20]. In the case of PAHs, degradation decreases in the order alkane > branched chain alkanes > low molecular weight aromatics > cycloalkanes [17]. It should be noted however that some pollutants are resistant to biodegradation (recalcitrant, i.e., resistant to degradation) they are degraded at very low pace even if the right microbial population and conditions are present.

3. Microbial bioreactors in bioremediation

Several laboratory, and pilot bioremediation studies have been done using microbial (fungi and bacteria) bioreactors [6, 8, 17, 18, 20]. Bioreactor technologies may offer effective means for treatment of many contaminants in groundwater, soil and air [4, 5, 7, 12]. The bioreactor type of choice for any application should be easy to operate and maintain for the selected purpose and application. **Table 1** presents some of the studies that involved the use of bioreactors in bioremediation. Flexibility to design bioreactor tailor made for different processes and remediation applications makes the use of bioreactors in bioremediation attractive [9]. The design should accommodate high biomass from cell growth, supply of necessary nutrients and also removal of waste components from the system. A description of some bioreactor types and their application is given in Sections 3.1–3.7.

3.1 Slurry phase bioreactors

Slurry phase bioreactors, as the name implies treats polluted media that is within a slurry phase. Alternative names are bio-slurry reactors and slurry phase biological treatment. Slurry bioreactors offer an *ex situ* environmentally friendly way for remediating mostly soils and sediments from petrochemical hydrocarbons, tars, creosotes, chlorinated solvents, herbicides, pesticides and explosives or when a solid substrate that is formulated into a slurry is used [4, 6, 25, 26]. Hydrophobic nature

Bioreactor type	Application details	Reference(s)
Packed bed	Different fungi and bacteria used for remediation of organochlorine pesticides, PAHs, pharmaceuticals, amines, and textile dyes. Packing material varied from organic material (sawdust, wood chips) to inert solid materials (polyurethane foam, poraver stones); chlorinated aliphatic compounds	[14, 17, 21–23]
Fluidised bed	Treatment of pharmaceuticals using fungi	[20, 22]
Two-phase partitioning	Benzene biodegradation by cow dung microflora	[24]
Slurry phase	Bacterial and fungal remediation of soil from VOC, organochlorines, PAHs, 2,4-dichlorophenoxyacetic acid	[4, 6, 25, 26]
Suspended carrier	Fungi used for remediation of organochlorine pesticides, PAHs, textile dyes.	[21]
Up-flow anaerobic stage reactor (UASR)	Bacterial degradation of tylosin	[16]
Membrane bioreactor	Textile dye in waste water; pharmaceuticals, 1,2-dichloroethane, 1,2-dichlorobenzene and 2-chlorophenol groundwater; metal recovery	[27–31]
Air lift	Textile dye effluent decolorization by fungi, olive mill effluent, cellulose industry bleaching effluent	[15, 32, 33]
Biotrickling filter	Municipal waste water, brewery waste, olive oil mill waste water, VOC contaminated air	[32, 34]
Upflow Anaerobic Sludge Blanket	Potato waste water, BTEX	[9, 35]
Sequence batch reactor	Nanosilver, Nanofullerenes	[36]
Continuous flow Bioreactor	PCP and creosote by some <i>Pseudomonas</i> species	[37]
Nonisothermal bioreactors	Degradation of phenol by fungal laccase	[38]
Continuously stirred tank bioreactor (CSTR)	For hydrocarbon-rich industrial wastewater effluents by mixed microbial cultures, petroleum hydrocarbon	[7, 8]

Table 1.
Studies that involved the use of bioreactors in bioremediation.

of most persistent chemicals makes them sorb to soil or sediments and not easily accessible for biodegradation.

Operation of the slurry reactor can be in batch, semi-continuous and continuous mode, with the batch process being the most common one [6, 26]. **Figure 1** shows an illustration of a simplified slurry reactor. Water is mixed with the contaminated solid matrix in suitable ratios and this enhances contact between microorganisms, pollutant, media and oxygen. Pollutants that are solubilized become more bioavailable. **Table 2** shows some of the studies that have involved the use of slurry phase bioreactors in bioremediation.

3.2 Partitioning bioreactors

Partitioning bioreactors are used in bioremediation when two phases need to be achieved, e.g., such as for organic solvents or water immiscible compounds in

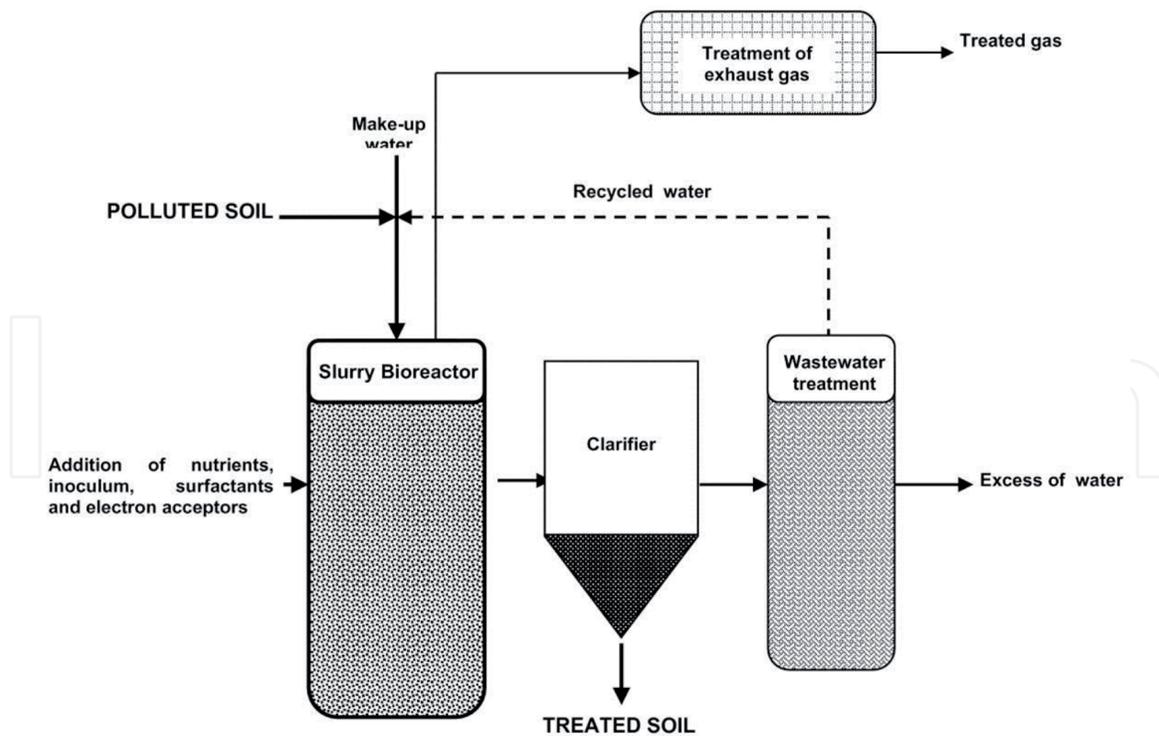


Figure 1.
Simplified slurry reactor [26].

aqueous solutions. Reactors are designed with the aqueous and organic phase, and can be single or multiphased [24]. With toxic hazardous waste, toxicity to degrading microorganisms is a problem. In partitioning bioreactors, there is a two-phase system where a water immiscible and biocompatible organic solvent is allowed to float on the surface of a cell containing aqueous phase [45]. This means that high amounts of hazardous waste dissolved in a solvent can be added to the reactor without the microorganism experiencing inhibitory concentrations of the pollutant [24, 45, 46]. A rigorous process involving selection of the solvent, taking into consideration the biological, physical, operational, environmental and economic factors is necessary in developing an efficient partitioning biotreatment system. Partitioning reactors find application in the remediation of toxic compounds from petrochemical industry such as benzene as well as VOC in waste gases of many industrial processes [45, 47, 48]. Angelucci et al. [49], successfully tested a continuous two-phase-partitioning reactor in the treatment of tannery wastewater. Several other studies involving phase partitioning bioreactors are described [24, 45–50].

3.3 Stirred tank bioreactors

A continuous stirred tank bioreactor consists of a cylindrical vessel with motor driven central shaft that supports one or more agitators (impellers). Stirred tank bioreactors are the predominantly used design for submerged cultures. Stirred tank bioreactors are mechanically agitated where the stirrers are the main gas-dispersing tools and provide high values of mass transfer rates coupled with excellent mixing. Advantages of the STR include the efficient gas transfer to growing cells, good mixing of the contents and flexible operating conditions, besides the commercial availability of the bioreactors. The main shortcoming of the stirred tank bioreactor is its mechanical agitation which requires energy and stirring can cause shear strain on microbial cells.

Gargouri et al. [7] evaluated the use of a continuously stirred tank bioreactor (CSTR) in the treatment of hydrocarbon-rich industrial wastewaters and achieved

Pollutant	Microorganism(s)	Bioremediation details	Reference(s)
Petroleum hydrocarbons in oil sludge	Indigenous microbial consortium	24% biodegradation of Total Petroleum Hydrocarbon in oily waste	[39]
2,4,6-trinitrotoluene (TNT)	Mixed soil bacteria under anoxic/microaerophilic conditions	99% of 10,000 mg kg ⁻¹ was degraded in 82 days under co-metabolism with molasses	[40]
PAHs in creosote	Degradation by <i>Pseudomonas fluorescens</i> , <i>Pseudomonas stutzeri</i> , and an <i>Alcaligenes</i> species	93.4% of creosote degraded in 12 weeks	[41]
Explosives 2,4,6-trinitrotoluene (TNT) and 2,4,6-trinitrobenzene (TNB)	Selected Gram positive bacterial isolates	Complete removal of the explosive after 80 days	[42]
Hexachlorocyclohexane (HCH)	White rot fungi <i>Bjerkandera adusta</i>	Maximal degradations of 94.5, 78.5 and 66.1% were attained after 30 days for the-HCH isomers, respectively	[4]
High molecular weight PAH in soil	PAH-degrading consortium	Pyrene degraded at 19 mg L ⁻¹ day ⁻¹ , chrysene and benzo[a]pyrene respectively at 3.5 and 0.94 mg L ⁻¹ day ⁻¹ .	[43]
Chlorpyrifos	Enriched indigenous soil microorganism	Degradation of 48% in aerobic and 31% in anaerobic soil slurries	[44]

Table 2.
 Some examples of remediation studies in slurry phase bioreactor.

successful bioremediation using an acclimatized microbial consortium. The residual total petroleum hydrocarbon (TPH) decreased from 320 –8 mg TPH l⁻¹. The reactor used is shown in **Figure 2**. Bi [51], applied a continuously stirred tank reactor for bioremediation of ethanol, toluene and benzyl alcohol by *P. putida*.

3.4 Biofilters

A basic biofilter bioreactor consist of a large media bed where pollutants are passed through and get degraded by the microorganisms. Biofilters are amongst the oldest environmental bioremediation techniques. Biofilters are used mostly in waste water treatment as well as in the control of air pollution [34, 52, 53]. A number of materials are used for bed media such as peat, composted yard waste, bark, coarse soil, gravel or plastic shapes. A typical example of a biofilter is the trickling filter which finds extensive application in the treatment of different liquid effluents or waste waters or waste that is constituted into liquid. A trickling filter is usually a round, vertical tank that contains a support rack and is filled with aggregate, ceramic or plastic media and in the middle of the tank is a vertical pipe that has a rotary connection with spray nozzles on the top end [34]. A spray arm is attached to the rotary connection and has spray nozzles installed along its length for

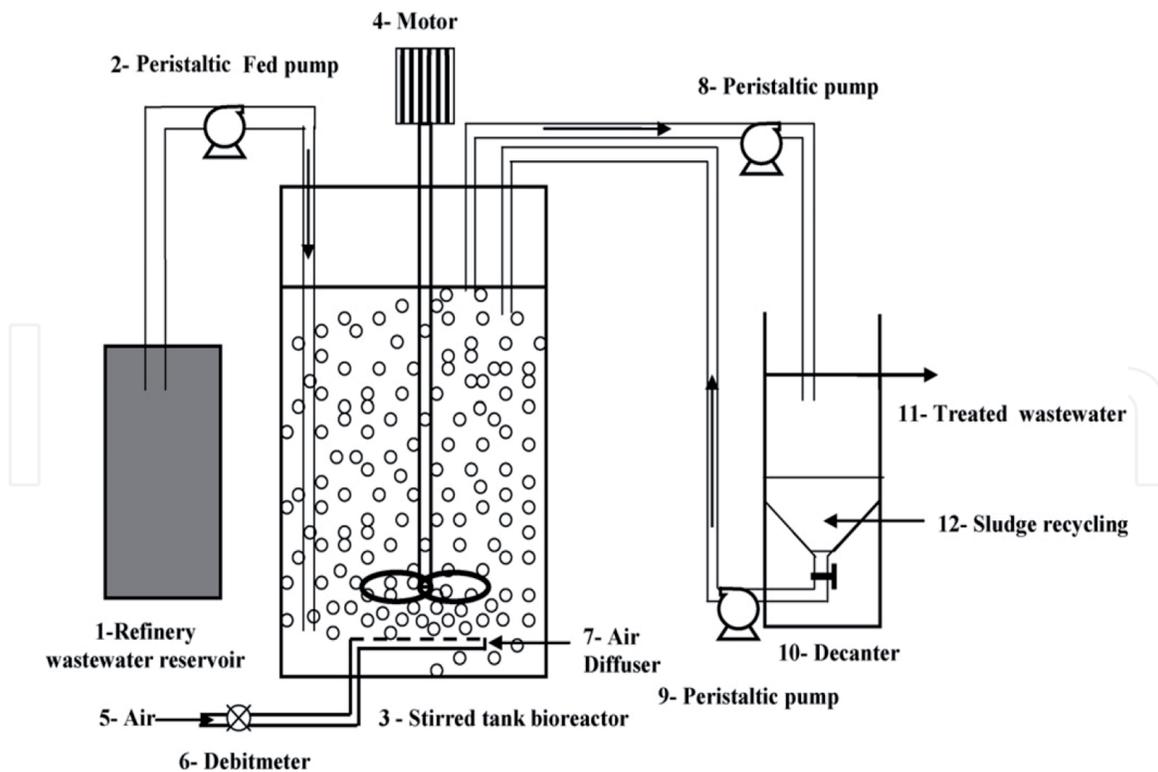


Figure 2. Schematic diagram of the aerobic continuously stirred tank bioreactor (CSTR) used for continuous experiments [7].

distribution of the waste water. Microorganisms grow in biofilm forms on the packing material surface and are responsible for the degradation of the pollutants from the effluent. Schmidt and Anderson [34] described the use of a trickling biofilter in the removal of high concentrations of 1-butanol from contaminated air. The potential application of the biotrickling filter in industrial off gas treatment was evaluated in the removal of high concentrations of 1-butanol from contaminated air with efficiency exceeding 80% for butanol concentrations of $0.4\text{--}1.2\text{ g m}^{-3}$ [34]. The laboratory-scale perlite-packed biotrickling filter was operated for 60 days and demonstrated effective and efficient removal of butanol concentrations up to 4.65 g m^{-3} with a maximum elimination capacity of $100\text{ g m}^{-3}\text{ h}^{-1}$ [34].

3.5 Packed bed bioreactors

Packed bed bioreactor systems provide for microbial growth on fixed film substrata. In order to obtain compact reactors and ensure greater treatment reliability, fixed film reactors are used. They offer the advantage that dilute aqueous solutions can be remediated at high biomass without the need to separate biomass and the treated effluent [13, 54]. In packed bed biofilm biotreatment processes, unlike suspension cultures there is no need to incorporate special measures such as centrifugation and membrane filters to retain the biomass. This feature makes the use of packed bed reactors particularly appropriate in bioreactors systems where large substrate—flow through is required. The concentration of cells in a given volume may be increased, a factor that leads to enhanced efficiency/productivity of the bioreactor and decreased volume of bioreactors [55]. While high biomass concentrations can be easily maintained, the medium to biofilm mass transfer of substrate is the rate limiting process in packed bed bioreactors [54, 56]. Within the biofilm there are considerable differences in the microorganisms' microenvironment, depending on the distance from the surface of the biofilm [54]. Substrates such as

oxygen, carbon and nitrogen sources have to cross the biofilm—liquid interface by diffusion, thus a diffusion gradient occurs. To calculate the kinetics of conversion in the biofilm processes, two important processes that occur in the system are considered and these are (i) transport of solutes over the biofilm and (ii) combined reactions and diffusion inside the biofilm [54]. In the packed bed reactors, development of excess microbial biomass also occurs leading to hydraulic channeling or loss of interstitial fluid volume. To overcome the severe constraints of hydraulic hold up within the interior of the reactor extra-capillary space transverse flow bioreactors were developed [57].

Selection of suitable substances as packing materials is an important consideration. Materials that have been used include nylon web, polyurethane foam, silicone tubing, sintered glass, porous ceramics, propylene, stainless steel, agarose and agar gel beads [58–67]. The ideal support should be chemically inert in physiological growth medium, rigid and porous to facilitate mycelial attachment and re-usable after removal of the fungus. **Figure 4** shows a Simplified diagram of a laboratory based packed bed bioreactor. Examples of remediation studies in packed bed reactors are given in **Table 3**.

3.6 Airlift bioreactors

Airlift bioreactors can provide an attractive treatment alternative for treatment of gaseous or volatile air pollutants. Frequently, the most limiting factor in the performance of these reactors is that they are susceptible to being limited by gas-liquid mass transfer and by poor mixing of the liquid phase, particularly when they are operating at high cell densities [68, 69]. The bioreactor performance is dependent on the pumping (injection) of air and the liquid circulation. The airlift bioreactor can have a forced

Support	Experimental study details	References
Polyurethane foam	Anaerobic fixed film horizontal flow bench scale reactor. Benzene, toluene, ethylbenzene, and xylene, BTEX removal with efficiency of 75–99% in 11.4 hrs	[58]
Laterite stones	Microbial consortium anaerobic degradation of textile azo dyes, 61.7% degradation of 55 $\mu\text{g mL}^{-1}$ of simulated effluent dye.	[59]
Coconut shell bio-char	Congo red dye degradation in batch and continuous packed bed bioreactors by <i>Brevibacillus parabrevis</i> . A 95.71% removal of in 6 days of 150 ppm dye.	[60]
Polyurethane foam	Bacterial degradation of malathion in batch and continuous packed bed bioreactors, removal at 89% for up to 145.4 mg L^{-1} day ⁻¹	[61]
Wire Mesh	Fungal degradation of textile effluent	[62]
Wood chips	Chlorophenol degradation by <i>Phanerochaete chrysosporium</i>	[63]
Sugarcane bagasse	Degradation of dyes and industrial effluents by <i>Garnoderma weberianum</i> B-18 immobilized in a lab-scale packed-bed bioreactor. 55–98% for different dyes tested	[64]
Celite	Perchlorate-Contaminated groundwater 800 $\mu\text{g L}^{-1}$ reduced to less than 4 $\mu\text{g L}^{-1}$ at 0.3 h retention time	[66]
Polyurethane foam	Biodegradation of an actual petroleum wastewater by an immobilized biomass of <i>Bacillus cereus</i>	[66]
Polyurethane foam and alginate beads	Benzene biodegradation <i>Bacillus</i> sp. M3 at 84 in alginate beads and 90% on polyurethane foam within 9 days	[67]

Table 3.
 Some examples of remediation studies in packed bed reactors.

flow in an internal or external loop as shown in **Figure 5**. Specific volatile organic chemicals may be completely degraded by a microorganism at normal temperature and pressure without producing a second polluted byproduct [70]. Nikakhtari and Hill [68], applied an External Loop Airlift Bioreactor with a small amount (99% porosity) of a stainless steel mesh packing inserted in the riser section for bioremediation of a phenol polluted air stream. Phenol removal of 100% was achieved using the bacterium *Pseudomonas putida*, and at a phenol loading rate of $22,160 \text{ mg h}^{-1} \text{ m}^{-3}$, thus demonstrating the novelty and potential VOCs bioremediation application of the reactor at high loading rates. **Figure 5** presents a schematic diagram of airlift bioreactor. Several other studies involving the use of airlift bioreactors [19, 69–71].

3.7 Membrane bioreactor

Membrane bioreactors (MBR) combine the use of a membrane that forms a filtration system and the biological process. The membrane provides a physical barrier that separates the liquid from the solid and ensures retention of the solids and good quality effluent. The quality of the treated effluent from the membrane bioreactor is of high quality than that achieved by employing other techniques, enabling optimal functioning of the secondary treatment system [72, 73]. MBR offer the advantages that often smaller tank size is used and filtration function of the membrane ensures that solids are separated from treated effluent. Membrane fouling has been recognized however as a major drawback in the application of membrane bioreactors in bioremediation. Also membranes are often expensive thus making the process costly. Development

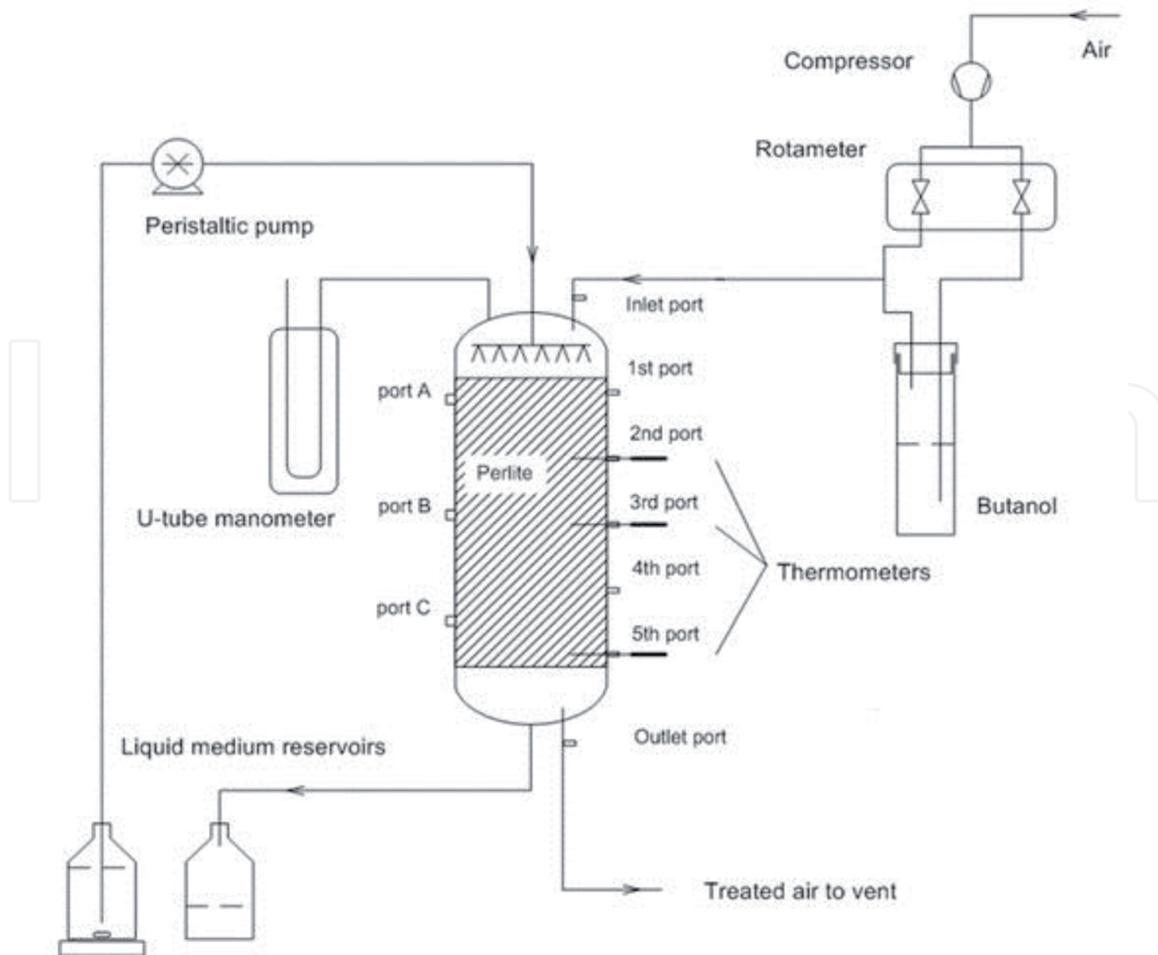


Figure 3. Schematic diagram of biotrickling filter [34].

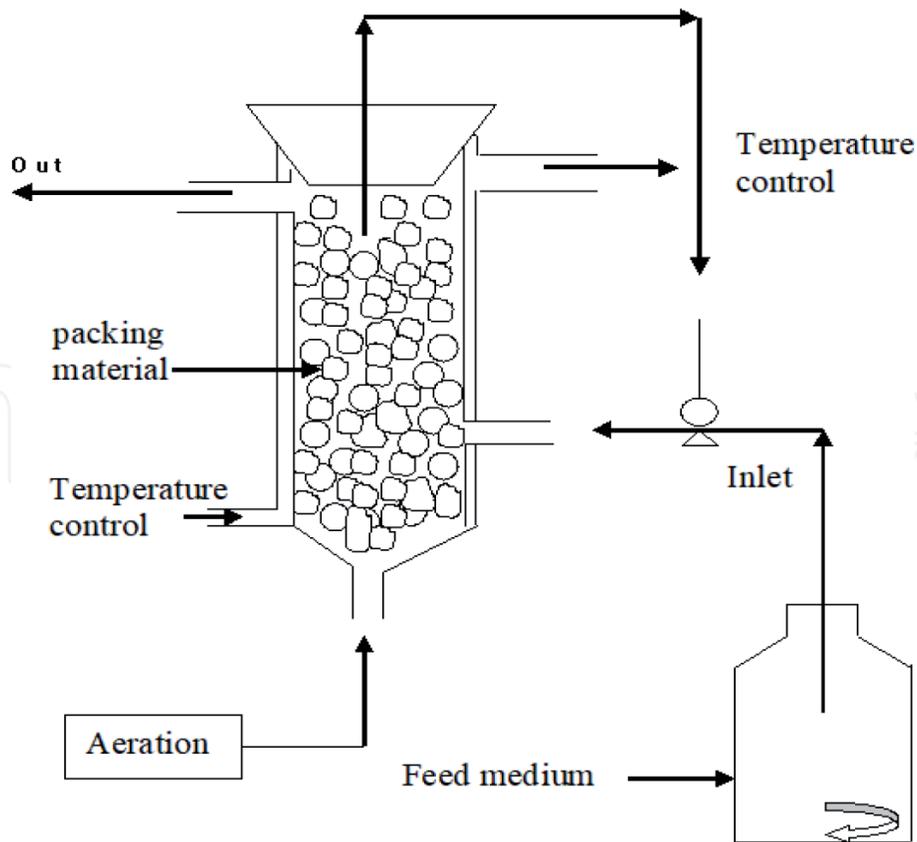


Figure 4.
Simplified diagram of a laboratory based packed bed bioreactor [21].

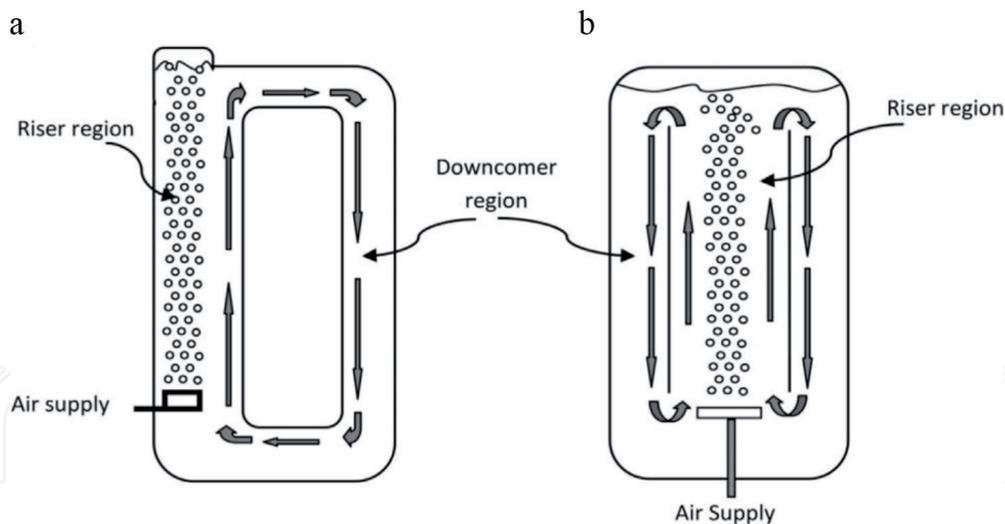


Figure 5.
Schematic diagram of airlift bioreactor with (a) external recirculation and (b) internal recirculation [15].

of low cost membrane filters is an ongoing feature in the science of MBR [72]. MBR reactors have been used in the biological treatment of domestic and industrial waste water. MBR have been evaluated in the remediation of pentachlorophenol in concentration ranges that occur in waste water [73], textile waste water [27], 1,2-dichloroethane, 1,2-dichlorobenzene and 2-chlorophenol [30].

3.8 Other bioreactors in bioremediation

Due to flexibility in bioreactor designs, the configuration of reactors is numerous. While an effort has been made here to describe some of the common

bioreactors used for different bioremediation applications, several other bioreactor types have not been discussed. These include the UASB which find major application in anaerobic digestion of waste waters as well as solid wastes, bio-scrubbers which are applied in off gas air pollution control, continuous stirred tank reactors as well as rotating contactor reactors.

4. Conclusions

It is evident that a wide range of microbial bioreactors have been developed and evaluated in the bioremediation of a wide range of pollutants in water, air and soil. Also a wide range of pollutants in physical and chemical properties are amenable to microbial degradation. Very diverse microbial species have the capability of pollutant degradation naturally and the use of well-developed optimized microbial bioreactors ensure improved rates of degradation when compared to degradation that happens *in situ* in the environment under natural environmental conditions.

Conflict of interest

No conflict of interest is declared.

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