Application of Biofilms on Remediation of Pollutants – An Overview

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ABSTRACT

During the last few decades, extensive attention has been paid on the management of environmental pollution caused by hazardous pollutants such as heavy metals and various xenobiotic compounds. Biofilms are structured microbial communities in which the microbial cells irreversibly attach to a surface or interface and become embedded in a matrix of extracellular polymeric substances produced by these cells. Biofilms have been found to be suitable for the remediation of pollutants because of their high microbial biomass and ability to immobilize pollutants. Biofilm research in the natural environment of soil, sand, sediments and wetland vegetation has revealed the potential of biofilm having capability to treat wastewaters bearing several pollutants. This article provides an overview on the role of biofilms for the remediation of various pollutants from environment which will provide insights into this research frontier.

Key words: Biofilm, Bioremediation, Extracellular polymeric substances (EPS), Heavy metals, Xenobiotics,

INTRODUCTION

Terrestrial and aquatic environments are contaminated with various kinds of pollutants. Among these, Total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs) and pesticides from anthropogenic sources pose a risk to human health [1]. Traditional remediation methods of polluted sites include soil excavation and transport, off-site treatment by solvent extraction, thermal alkaline dechlorination, incineration or land filling [2]. But these techniques are costly, detrimental for the environment and in many cases, practically infeasible due to the range of contamination [3]. In addition, the anthropogenic emission of dissolved toxic metals into the aquatic environment has also aroused serious public concern [4]. The main technologies used for metal removal include chemical precipitation, electrochemical deposition, evaporation, membrane process, ion exchange and activated carbon adsorption [5, 6]. However, the application of these methods is often limited due to their inefficiency, high capital investment and operational costs. Therefore, there is a growing need for the development of novel, efficient, eco-friendly and cost effective strategy for the remediation of the environmental pollutants.

Recently biofilms have become a focus of interests for the researchers in the field of bioremediation of xenobiotic compounds. In the year 1978, the term ‘biofilm’ was coined and described by Costerton et al. [7] Biofilms are clusters of microbial cells that are attached to a number of different surfaces such as natural aquatic and soil environments, living tissues, medical devices or industrial or portable water piping systems [8, 9]. It can be defined as an aggregation of bacteria, algae, fungi and protozoa enclosed in a matrix consisting of a mixture of polymeric compounds, primarily polysaccharides generally referred as extracellular polymeric substances (EPS). Microbial community has been found to be protected from environmental stresses using biofilms [8, 10, 11].
Biofilms give support to the high density of microbial biomass which facilitates the mineralization processes by maintaining optimal pH conditions, localized solute concentration and redox potential in the vicinity of the cells. This is achieved by the unique architecture of the biofilm and controlled circulation of fluids within it [12, 13]. The phenomenon of mass transport in biofilms is influenced by its structure which depends upon the local availability of the substrates. Solute transport in biofilm is driven by convective transport within pores and water channels and also by diffusion in the denser aggregates [13]. Biofilms undergo dynamic changes during their transition from free living organisms to sessile biofilm cells, including the specific production of secondary metabolites and a significant increase in the resistance towards biological, chemical and physical assaults [14].

Studies of biofilm formation have primarily focused on biofilms formed by a single species of microorganism [15, 16, 17]. In natural environments, however, biofilms are thought to be composed of more than one species. Indeed, several investigators have done pioneering work on mixed-species biofilm formation [18, 19, 20].

Biofilm formation
In most habitats—both natural and artificial—the majority of microbial populations form biofilms on solid surfaces [21, 22]. Microorganisms in biofilms become highly differentiated from those in the planktonic state [23] and often exhibit a developmental sequence, forming complex, multicellular structures (microcolonies) which become surrounded by a network of water channels [24]. At present, the consensus model in biofilm research proposes that microbial community development on surfaces is a stepwise process involving adhesion, growth, motility and extracellular polysaccharide production [25]. Once an initial biofilm is established, cell to cell communication (i.e. quorum sensing) via extracellular signaling molecules regulates further modification and development of the biofilm [26]. Recently *In vitro* model of bacterial biofilm formation on polyvinyl chloride biomaterial (PVC) has been reported [27]. Bacterial biofilm formation on the surface of PVC material was found to be a dynamic process with maximal thickness being attained at 12–18 h. These biofilms became mature by 24 h.

Although microbial biofilms often exert various deleterious effects in natural, clinical or industrial environments, they may be useful in biodegradation of complex waste materials. Biofilm-mediated bioremediation presents a proficient and safer alternative to remediation with planktonic microorganisms because cells in a biofilm have a better chance of adaptation and survival (especially during periods of stress) as they are protected within the matrix [28]. Owing to the close, mutually beneficial physical and physiological interactions among organisms in biofilms, the usage of xenobiotics is accelerated and consequently, biofilms are used in industrial plants to help in immobilization and degradation of pollutants.

Bioremediation of pollutants using biofilms
Bioremediation is the application of biological processes for the removal of hazardous pollutants present in the environment [29]. It is the process of using *in situ* or *ex situ* microorganisms to cleanup a contaminated site [30]. Biofilms can be applied for the bioremediation of waste waters. There are successful examples of the positive use of biofilms that are called beneficial biofilms which offer their member cells several benefits, among which protection of environment from the hazardous effects of toxic pollutants stands first. Biofilm based reactors are commonly used for the treatment of large volume of industrial and municipal wastewaters. During the last few decades, biofilm reactors have become a focus of interests for the remediation of xenobiotic compounds [31, 32].

The main biofilm reactors are categorized according to the methods used such as Biofilm fluidized bed (BFD), Upflow sludge blanket (USB), Expanded granular sludge blanket (EGSB) and Biofilm airlift suspension (BAS) [33]. Recently, Harvey et al. [34] have reviewed the research work involving aerobic and anoxic biofilm treatment of water pollutants using various reactor types viz. trickling filters, rotating biological contactors, submerged bed biofilm reactors, membrane bioreactors, fluidized bed reactors and immobilized cell reactors.

Remediation of heavy metals
The potential environmental health hazards generated by the presence of toxic heavy metal contaminants in industrial effluents are well known. Heavy metal remediation can be achieved by immobilization, concentration and partitioning to an environmental compartment, thereby minimizing the anticipated hazards [35, 36]. There are reports on the application of biofilms for the removal of heavy metals. Recently, bioremoval of Cr(III) using bacterial biofilm in continuous flow reactor have been reported [37]. Biofilm developed using consortium of *Bacillus subtilis* and *Bacillus cereus* on coarse sand was able to remove 98 % of Cr(III). The ability of a biofilm of *Escherichia coli* supported on NaY zeolite for the removal of Cr(VI), Cd(II),Fe(III) Ni(II) from wastewater was

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reported. The results of the study showed that the biofilm tested was very promising for the removal of metal ions from effluents [38]. Same group of workers reported the removal of Cd(II), Cr(VI), Fe(III) and Ni(II) from aqueous solutions by *E. coli* biofilm supported on kaolin [39]. The biosorption performance in terms of uptake followed the sequence: Fe (III) > Cd(II) > Ni(II) > Cr(VI). Rabei et al. [40] reported the biosorption of hexavalent chromium using biofilm of *E. Coli* supported on granulated activated carbon (GAC). The results demonstrated that biofilm supported on GAC which prepared by impregnation method could be used as promising biosorbent for the removal of Cr(VI) ions from aqueous environment. Heavy metal removal from aqueous solution by wasted biomass from a combined As- biofilm process has been reported [41]. This study evaluated the capability of metal biosorption by wasted biomass from a combined anaerobic anoxic – oxic (A2O) – biofilm process with simultaneous nitrogen and phosphorus removal. Zinc, cadmium and nickel were rapidly adsorbed in 20 min by the harvested sludge from a continuous flow pilot plant. Brandy et al. [42] reported the zinc sorption by bacterial biofilm. In this study, the metal-complexing functional groups present within a suspension of bacterial cell aggregates embedded in extracellular polymeric substances (EPS) were identified. Zn adsorption experiments were conducted at pH 6.9 with the freshwater and soil bacterium *Pseudomonas putida*. The adsorption data were fitted with the van Bemmelen-Freundlich model. The molecular speciation of Zn within the biofilm was examined with Zn K-edge extended X-ray absorption fine structure (EXAFS) spectroscopy. Cadmium removal from environmental water by biofilm covered granular activated carbon was reported [43]. The goal of this research was to determine the potentiality of Granular activated carbon (GAC), biofilm and biofilm covered GAC (BAC) columns to treat low concentration cadmium bearing water streams. It was found the BAC was more efficient than GAC for the removal of cadmium from water environment. Removal of heavy metals viz. Cd, Zn, Cu, Pb, Hg, Ni and Co from large volume of wastewater using moving bed sand filter technology was reported by Diels et al [44]. A biofilm was formed on the sand grains after inoculation with heavy metal resistant bacteria which was able to biosorb or to bioprecipitate heavy metals.

Costley and Wallis [45] investigated the efficiency of biofilm of a rotating biological contactor (RBC) for the treatment of wastewaters contaminated with cadmium, copper and zinc in multiple sorption –desorption cycles. The removal pattern observed in the initial cycle was Cu> Zn> Cd which was repeated in the subsequent cycles. They observed the high metal sorption capacities particularly for copper which indicated that biofilm of (RBC) could be used as a tool for removal and recovery of metals from wastewaters. Same group of workers noted the ability of the biofilm of a three –stage rotating biological contactor (RBC) to treat wastewater containing Cd, Cu and Zn. The system successfully removed the metals in the order Cu> Zn> Cd with removal capacities of approximately 73, 42 and 33 % respectively [46]. Scott et al. [47] reported a comprehensive biofilm of bacteria *Pseudomonas sp.* (NCIMB 11592) bound together in an excreted polysaccharide matrix and attached to granular activated carbon (GAC) which was shown to enhance both rate and quantity of metal uptake from contaminated solution. This system employing GAC as a biofilm support was demonstrated to both entrap metals and also adsorb other contaminants. Electron micrographs illustrated an open film that provided a high surface area for biosorption of metal ions such as cadmium, copper, zinc and nickel. Studies provided data on both equilibrium loadings ( mg metal /g adsorbent) and adsorption rate coefficients.

**Remediation of toxic compounds**

Over the last few decades, enormous quantities of synthetic chemicals have been released into the environment. They are posing serious problems being xenobiotic and highly hazardous, such as hydrocarbons, phenols, PCBs and other recalcitrant and persistent aromatics. EPA list of some organic primary pollutants injected into the environment by human activities include chlorinated phenols, dichlorobenzene, hexachloroethane, Napthalene, polynucleated aromatic hydrocarbons (PAHs) viz. toluene, benzopyrine, polychlorinated biphenyls, hexachlorocyclohexane, , pesticides like aldrin, DDT, endrin etc [48]

Release of hydrocarbons into the environment whether accidental or due to human activities is a major cause of water and soil pollution [49]. Recently, we have reported the potential application of yeast biofilm formed on gravels which showed 97 % degradation of diesel oil over a period of 10 days [50]. The potential use of the biofilms for preparing trickling filters (gravel particles), for attenuating hydrocarbons in oily liquid wastes before their disposal in the open environment is suggested. This was the first successful attempt for ‘artificially’ establishing hydrocarbon degrading yeast biofilm on solid substrates. Rafida et al. [51] reported the removal of hydrocarbon compounds by using a reactor of biofilm in an anaerobic medium. The technique involved the use of biofilms developed on supporting material in a reactor, which used a Vertical Flow Biofilter (VFB) in an anaerobic condition. The reactor was a cylinder made of Poly Vinyl Chlorine (PVC), filled with layers of supporting materials. The lower part of the unit was filled with gravel, whereas the uppermost part was filled with small bottles made up of
Alkylphenol compounds (APs) are the most common environmental pollutants due to wide use and abroad existence in environment [67]. Steroidal hormones and alkylphenols were found to be attenuated by and accumulated or concentrated in biofilms on stream sediments. The tendency to concentrate the pollutants in biofilm in the natural environment can serve as negative function of providing the mechanism of entry of the pollutants into the aquatic organism food chain. This biofilm system may represent the viable means of reducing these pollutants in

Polyethylene Terephthalate (PET). The biofilms were then developed featuring a diversity of microorganisms mainly bacteria. The hydraulic retention time (HRT) of the reactor was found to be 6.25 days, which meant that the reactor was to be sampled every six days after water treatment. The total organic carbon (TOC) consumption in the water after treatment was 40 %, with the unit showing a hydrocarbon removal efficiency of 90 %.

Al-Awadhi et al. [52] described a method for artificially establishing biofilms rich in hydrocarbon degrading bacteria on gravel particles and glass plates. The microbial consortia in the biofilms included filamentous cyanobacteria, picoplankton and diatoms. Phototrophic microorganisms were the pioneer colony formers. In batch cultures, it was found that artificial biofilms showed remediation effect on crude oil contaminated sea water samples. The potential use of these biofilms was suggested for preparing trickling filters (gravel particles) and in bioreactors (glass plates) for removing hydrocarbons from oily liquid wastes before disposal in environment. Hydrocarbon degrading microbial consortia (bacteria and microalgae) immobilized in biofilms on gravel particles in the intertidal zone of the Arabian Gulf coast was reported [53]. Each gravel particle was found to be coated with about 100 mg of blue green biomass. The predominant photroph was the cyanobacteria Dermocarpella sp. and the most dominant hydrocarbon degrading bacterium in the consortium was Acinetobacter calcoaceticus. The biofilm coated gravel particles were used in 5 successive cycles of purification of oily sea water.

Chlorinated aromatic compounds are the most widespread contaminants of soil and ground water which are present in chemical industry effluents. They are carcinogetic at very low concentrations [53,54].To remove 2,4, dichlorophenol (DCP) from synthetic wastewater, a rotating perforated tube biofilm reactor was used which contained mixed microbial biomass of activated sludge supplemented with DCP degrading Pseudomonas putida. Nearly 100 % of the DCP was degraded [54]. Overall degradation efficiency was found to be in the range of 70-100 %. Complete degradation of 2,4,6 trichlorophenol and 2,3,4,6 tetrachlorophenol and pentachlorophenol was reported using Fluidized bed biofilm reactor through involvement of Pseudomonas sp. and Rhodococcus sp [55]. Chang et al. [56] reported the degradation of 2- chlorophenol using hydrogenotrophic biofilm under different reductive conditions. Degradation of 4- chlorophenol by a bacterial consortium using a granular activated carbon biofilm reactor was reported by Caldeira et al. [57]. A GAC biofilm reactor was also used for the continuous degradation of 4- chlorophenol by Carvalho et al. [58]. Biodegradation of polychlorinated biphenyls (PCBs) using three phase fluidized bed biofilm reactor was reported [59]. The biofilm was developed on cement balls and acclimatized to PCBs for two months by feeding the reactor alternately with PCB and biphenyl. The rate of PCB degradation was influenced by the long exposure of the biofilm to PCBs and the presence of mixed culture in the biofilm.

Nitroaromatic compounds are another group of xenobiotic compounds which are resistant to biodegradation and harmful metabolites are produced after microbial degradation [60, 61]. Gisi et al. [60] reported the degradation of 4,6 – dinitro- ortho- cresol in batch cultures and in fixed bed column reactors . Mixed culture was used for degradation of dinitrotoluene (DNT) in a fluidized bed biofilm reactor which was fed with aqueous solution of 2,4- DNT (40mg/L) and 2,6- DNT (10 mg/L). Degradation was found to be 98 % for 2,4 DNT and 94 % for 2,6 DNT [61]. There are reports on degradation of toluene in hollow fibre membrane biofilter reactor and continuously fed bioreactor using various aerobic and anaerobic bacteria isolated from secondary sludge wastewater [62, 63]. Toluene degradation percentages were found to be 84 % and 65 %. Kumar et al. [64] reported the degradation of toluene by Burkholderia vietnamiensis G4 in a Gas Phase Membrane Bioreactor. In this study, toluene was used as a model pollutant and the dynamics of living cells (LC) and dead cells (DC) of bacteria in a laboratory-scale biofilm membrane bioreactor for waste gas treatment was examined. An optimum toluene removal of 89% was observed at a loading rate of 14.4 kg m-3 d-1. A direct correlation between the biodegradation rate of the reactor and the dynamics of biofilm development could be demonstrated. This was the first report on biofilm development during gaseous toluene degradation in membrane bioreactor.

Aromatic amine compounds are toxic causing health hazards [65]. Biodegradation of aromatic amine compounds including aniline, para-diaminobenzene and para-aminophenol have been reported by Delnavaz et al. [66] using three moving bed biofilm reactors. Biodegradability of aromatic amines was proved by nuclear magnetic resonance system.

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wastewater. Biodegradation of steroidal hormones and alkylphenols by stream biofilms have been reported by Writer et al. [68].

Water pollution caused by branched alkyl benzene sulfonates (BAS) is a significant environmental problem in some countries. Hosseini et al. [69] reported the biodegradation of dodecylbenzene sulfonate sodium by Stenotrophomonas maltophilia biofilm. This study showed the main advantages of S. maltophilia biofilms on silanized glass beads.

Thiocyanate (SCN) is another toxic compound which is widely being used in many industries like photofinishing, herbicide and insecticide production, dyeing, acrylic fiber production, thiourea production, metal separation, electroplating, soil sterilization and corrosion inhibition. It is toxic to microorganisms at relatively low concentrations of 58–116 mg/L and thyroid function is depressed on chronic exposure to thiocyanate [70]. Jeong and Chung [71] reported the biodegradation of thiocyanate in biofilm reactor using fluidized-carriers. The study was carried out for the biological treatment of the wastewater containing highly concentrated thiocyanate. Microorganisms for thiocyanate biodegradation were isolated and the biofilm reactor charged with fluidized-carriers of tube chip type and employed. The isolated microorganisms were presumed autotrophs. Test was performed in a small-scale biofilm reactor and the maximum degradation was found to be 80 vol% of fluidized-carriers which was much higher than those observed in any other reactor systems.

Bioaccumulation of the herbicide diclofop in extracellular polymers and its utilization by a biofilm community during starvation was reported [72].

Lakshmi and Das [73] studied the removal of an emerging pollutant such as caffeine from the industrial wastewater using biofilm formed on gravels by the yeast, Trichosporon asahii. Maximum caffeine removal was noted when ‘artificially’ formed yeast biofilms were packed in the column which could efficiently degrade 95% of the caffeine present in the effluent after 48 h. Thus, the yeast biofilms can play an important role in the development of cost effective biodecaffeination process for the treatment of coffee processing industrial effluent.

Remediation of plastic wastes
Along with the advancement in technology and increase in global population, plastic materials have been found wide applications in every aspect of life and industries during the last few decades which have become the potential sources of environmental pollution [74]. Polyethylene, a xenobiotic polymer was under large-scale production since 1950s which has become a global problem today. Recently, degradation of thermally oxidized high-density polyethylene by the biofilm formed by the fungal species Aspergillus niger (ITCC No.6052) which was isolated from plastic waste dumpsite has been reported [74]. A visible increase in the growth of the fungi was observed on the surface of the polyethylene when cultured in minimal medium at 30°C and 120 rpm, for 1 month. Approximately 3.44% reduction (gravimetrically) in mass and 61% reduction in tensile strength of polyethylene was observed after 1 month of incubation with fungal isolate. Scanning electron microscope analysis showed hyphal penetration and cracks on the surface of polyethylene. A thick network of fungal hyphae forming a biofilm was also observed on the surface of the plastic pieces. The efficient biofilm formation on polyethylene surface by Aspergillus niger (ITCC no. 6052) was attributed to its high cell surface hydrophobicity which indicated the thermally oxidized polyethylene degradation potentiality of A. niger (ITCC no. 6052).

Degradation of polythene using algal biofilms has been reported [75]. Fifteen algal taxa, including Chaetophora, Coleochaete scutata, Coleochaete soluta, Aphanochaete, Gloeotaenium, Oedogonium, Oocystis, Oscillatoria, Phormidium, Chroococcus, Aphanothecce, Fragillaria, Cocconis, Navicula, and Cymbella were identified. C. scutata and C. soluta colony proliferation on the surface of polythene was clearly seen under scanning electron microscope. A biofilm producing bacterial strain (C208) of Rhodococcus ruber was isolated which could degrade polyethylene at a rate of 0.86% per week [76].

Gilan et al. [77] reported that the strain of Rhodococcus rubber (C208) utilized polyethylene films as sole carbon source and in liquid culture and formed a biofilm on the polyethylene surface and degraded up to 8% (gravimetrically) of the polyolefin within 30 days of incubation.

Remediation of synthetic dyes
Synthetic dyes being extensively used in various industries [78] have been reported as carcinogenic and mutagenic for aquatic organisms [79]. Thus, removal of dyes from waste water is still of a major environmental concern.
Compared to other pollutants, few reports are available on remediation of synthetic dyes using biofilms. Aerobic biodegradation of azo dyes in biofilms was reported by Jiang and Bishop [80]. Among the three azo dyes studied - Acid Orange 8, Acid Orange 10, and Acid Red 14 - only AO-8 degraded aerobically. The azo bond cleavage occurred very easily for all three dyes under anaerobic conditions. AO-8 removals ranged from 20% to 90%. Statistically designed experiments were used to characterize the response of pseudo-steady state biofilms. The presence of azo dyes, along with other factors such as COD loading, bulk-phase DO level and shear force, showed impact on biofilm accumulation. Zhang et al. [81] reported the biodegradation of Acid orange 10, 14 using laboratory scale rotating drum biofilm reactor. The biofilm forming organism was Methylosinus trichosporium. Remediation of the azo dye Everzol Turquoise Blue G was reported using the biofilm formed by Coriolus versicolor in laboratory scale activated sludge unit [82].

Table 1 summarizes the reported information on remediation of various pollutants using biofilm.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Biofilm forming Organisms/ culture</th>
<th>References</th>
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<tbody>
<tr>
<td>Heavy Metals</td>
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<tr>
<td>Cr(III)</td>
<td>Bacillus subtilis and Bacillus cereus</td>
<td>Sundar et al [37]</td>
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<td>Cr(VI), Cd(II), Fe(III), Ni(II)</td>
<td>Escherichia coli</td>
<td>Cristina et al [38]</td>
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<td>Cr(VI)</td>
<td>Escherichia coli</td>
<td>Rabei et al [40]</td>
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<td>Zn(II)</td>
<td>Pseudomonas putida</td>
<td>Brandy et al [42]</td>
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<td>Cu(II), Zn(II), Cd(II)</td>
<td>Activated sludge from A sewage</td>
<td>Costley &amp; Wallis [45]</td>
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<td>Cu(II), Zn(II), Cd(II)</td>
<td>Activated sludge from A sewage</td>
<td>Costley &amp; Wallis [46]</td>
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<tr>
<td>Cd(II), Cu(II), Zn(II), Ni(II)</td>
<td>Pseudomonas sp. NCIMB 11592</td>
<td>Scott et al [47]</td>
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<td>Toxic Compounds</td>
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<td>Diesel</td>
<td>Candida tropicalis</td>
<td>Chandran &amp; Das [50]</td>
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<td>Hydrocarbon compounds</td>
<td>Bacteria from sewage water</td>
<td>Rafida et al [51]</td>
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<td>Hydrocarbon compounds</td>
<td>Filamentous cyanobacteria, picoplankton and diatoms</td>
<td>Al-Awadi et al [52]</td>
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<tr>
<td>Hydrocarbon compounds</td>
<td>Cyanobacteria D. calceiopsis sp. and Acinetobacter calcoaceticus</td>
<td>Radwan &amp; Al-Hassan [53]</td>
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<td>2,4-dichlorophenol</td>
<td>Pseudomonas putida</td>
<td>Kargi &amp; Eker [54]</td>
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<td>2-chlorophenol</td>
<td>Anaerobic sludge from a sewage treatment plant</td>
<td>Chang et al [56]</td>
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<td>4-chlorophenol</td>
<td>Anaerobic consortium from rhizosphere of Phragmites australis</td>
<td>Caldeira et al. [57]</td>
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<td>Hydrocarbon compounds</td>
<td>Acinetobacter calcoaceticus</td>
<td>Carvalho et al. [58]</td>
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<td>Polychlorinated biphenyl (PCB)</td>
<td>Anaerobic bacteria isolated from secondary sludge wastewater</td>
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<td>4,6-dinitro-ortho-cresol</td>
<td>Bacterial culture</td>
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<td>Sludge from wastewater treatment Plant; various aerobic and bacteria</td>
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<td>Kumar et al [64]</td>
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<td>Pseudomonas sp. strain ST-4</td>
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<td>Dodecylbenzene sulfonate sodium</td>
<td>Stenotrophomonas maltophilia</td>
<td>Hosseini et al [69]</td>
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<td>Plastic Wastes</td>
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<td>Mathur et al [74]</td>
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<td>Chroococcus, Aphanathece, Fragillaria, Coccomis, Navicula and Cymbella</td>
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<td>Sivan et al [76]</td>
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<td>Synthetic Dyes</td>
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<td>Acid orange 10, 14</td>
<td>Methylosinus trichosporium</td>
<td>Zhang et al [81]</td>
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<td>Everzol Turquoise Blue G</td>
<td>Coriolus versicolor</td>
<td>Kapdan and Kargi [82]</td>
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**CONCLUSION**

Biofilm system is continuously drawing great attention for research. Based on the reports, it may be concluded that biofilms have the potentiality to remove heavy metals and other xenobiotic compounds from wastewaters and
natural waters containing low levels of pollutants. Moreover, the tendency to concentrate the pollutants in biofilm in natural environment can serve the negative function of providing a mechanism of entry of pollutants into the aquatic organism food chain. This review will provide an opportunity to reflect on the role of biofilm towards wastewater treatment and environmental research. Further research area needs to be extended on the focus of gene transfer within biofilms. Study of biofilm communities and gene transfer within biofilms would facilitate the development of better techniques for the bioremediation of polluted sites and wastewaters.

REFERENCES

[27] Z. Guang-qiang, Y. Lian-hua, H. Yun-chao, Y. Da-kuan, L. Li, Biochem Biophys. 61, 371–376