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Biotreatment potential of co-contaminants hexavalent chromium and polychlorinated biphenyls in industrial wastewater: Individual and simultaneous prospects

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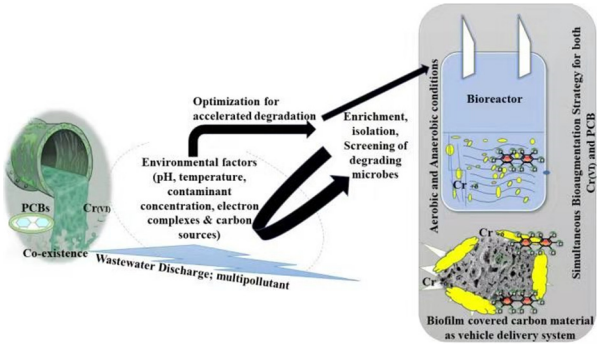
HIGHLIGHTS

- Industrial wastewater contamination is hazard for biotic and abiotic factors of the environment.
- Co-existence of Cr(VI) and PCBs in industrial effluents is a global problem.
- Numerous microbial species can degrade both Cr(IV) and PCBs individually.
- Simultaneous biotreatment of co-contaminated sites will be an effective bioremediation strategy.

GRAPHICAL ABSTRACT



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ABSTRACT

Co-existence of polychlorinated biphenyls (PCBs) and hexavalent chromium (Cr(VI)) in the environment due to effluent from industries has aggravated the pollution problem. Both contaminants can alter chemical interactions, processes and impair enzymatic activities in the ecosystem that results in negative impacts on aquatic and terrestrial life. Previously, research has been performed for the fate and transfer of these contaminants individually, but simultaneous removal approaches have not received much attention. Cr(VI) exists in a highly toxic form in the environment once released, whereas location of chlorine atoms in the ring determines PCBs toxicity. Lower chlorinated compounds are easily degradable whereas as high chlorinated compounds require sequential strategy for transformation. Microorganisms can develop different mechanism to detoxify both pollutants. However, occurrence of multiple contaminants in single system can alter the bioremediation efficiency of bacteria. Use of metal resistance bacterial for the degradation of organic compounds has been widely used bioaugmentation strategy. Along with that use of sorbents/bio sorbents, biosurfactants and phytoremediation approaches have already been well reported. Bioremediation strategy with dual potential to detoxify the Cr(VI) and PCBs would be a probable option for simultaneous biotreatment. Application of bioreactors and biofilms covered

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Simultaneous
Biotreatment

organic particles can be utilized as efficient bioaugmentation approach. In this review, biotreatment systems and bacterial oxidative and reductive enzymes/processes are explained and possible biotransformation pathway has been purposed for bioremediation of co-contaminated waters.

Contents

1. Introduction

The contaminants polychlorinated biphenyl (PCBs) and hexavalent chromium Cr(VI) have been extensively applied in electrical equipment, transformers, flame retardants, plasticizers, petroleum (oil and coal), pigment oxidants, steel, fertilizers, leather tanneries and paints (Golding, 2016; Jaishankar et al., 2014). Although banned since 1979 and categorized as "Persistent Organic Pollutant" by the Stockholm Convention, PCBs are still present in the environment due to extensive use in previous decades, as by product during different natural or industrial transformation processes and limited treatment in industrial wastewater (Carpenter, 2006). PCBs belong to the organochlorine family and possess various properties including inflammability, electrical resistance, insulating properties, and stability against heat and pressure which causes various human health hazards once released into the environment. Most common sources of PCBs are improper disposal of waste, stormwater, sewerage, leaks from electrical equipment etc. (Tehrani and Van Aken, 2014). Once in the environment, they can be transported over long distances due to their strong adsorption behavior with soil. In the environment, PCBs are health hazard to animals, plants and humans (Robertson and Hansen, 2015). Positioning of the chlorine atoms along the carbon ring decides persistence and bioconcentration in environment. The level of toxicity and ability of PCBs to adsorb to surface depends on the location of chlorine atoms in the structure (Anyasi and Atagana, 2011). PCBs have shown to cause mild liver damage in animals upon long term exposure to feed stock contaminated with PCB leading to carcinogenic effects and eventually death as well as cause mortality in seabirds (Borja et al., 2005). Studies suggested that during egg shell development, PCBs can inhibit calcium deposition which leads to inadequate strong shells and premature damage (Ma and Sassoon, 2006). Anti-estrogen effects also shown to harm the male reproduction of birds and animal species (Jeng, 2014).

Cr(VI) also has an extensive application in industries including plastics, inks and paints. In leather tanning, Cr(VI) is used as preservative for washing for clearing the skins and hides, which ends up into water bodies due to extensive usage (Thanikaivelan et al., 2005). Addition of chromates as anticorrosive agents to surface coatings and electroplated onto metal parts is common practice. Chromium oxidation states varies from −4 to +6 whereas +3 and +6 states are most frequently observed in the environment due to their stability (Lunk, 2015). The Cr(VI) oxidation state is more toxic and persistent in soil and aquatic system based on their environmental chemistry including redox reaction, dissolution and adsorption/desorption (Cheung and Gu, 2007). Cr(VI) can be actively taken up by plant cells by carrying essential anions whereas the uptake of Cr(III) is passive or inactive (Pereira et al., 2013). Cr(VI) is stable in soil and aquatic system, but it is reduced to the trivalent state via interaction with organic matter biota, soil and water.

Co-contamination with both types of pollutants is common throughout the world. Similarly, different types of pollutants have independent complex phenomena for their treatment. Which resulted in accumulation of both Cr(VI) and PCBs into different components of ecosystem. This also gets complicated by the fact that presence of heavy metals can halt several microbial processes that includes bacterial metabolism, growth and aerobic degradation of several organic compounds (Sandrin and Maier, 2003). Rate of heavy metal influx into environment is far greater that their reduction by natural processes which demands a more dynamic strategy for remediation (Agnello et al., 2016). Coupling the adopted strategy, to reduce heavy metals, with additional degradation of organic compounds can be an effective way for dealing with multi-contaminated industrial sites. As the first step in bioremediation of Cr(VI) and lower chlorinated compounds is reduction process, biotreatment of both contaminants can be achieved by similar bacterial strains. Cr (VI) can also act as an electron acceptor in transformation of lower forms and lower-chlorinated PCB congeners under aerobic conditions. Therefore, reduction of Cr(VI) along with oxidation of monochlorinated biphenyl is possible in single system. This potential solution needs further evaluation in a simultaneous bioremediation system of metals and organic compounds. Which can be exploited

for development of simultaneous approach for such polluted water bodies. This review will give an overview of the possibility of using the same strains, enzymatic process or method for the simultaneous biotreatment of Cr (VI) and PCBs.

2. Toxicity of PCBs and Cr(VI)

Persistence of PCBs in environment along with resistance to metabolism and accumulation into lipids have induced concerns related to their toxicity for biotic components of the ecosystem. The prolonged exposure of PCBs has been reported to cause harmful effects on the aquatic and terrestrial environment as well human health and wildlife. The toxicity of PCB in environment varies among the congeners and placement of chlorine atoms (Robertson and Hansen, 2015). The high molecular weight chlorinated compounds bioaccumulate in greater concentrations than low molecular weight ones among animal and human tissues due to higher KOW values which depend upon the physical characteristics of the sediment i.e., fine sediment particles have higher PCBs concentration due to large surface area. Impacts of PCBs on human health were studied extensively but risk assessment-based studies have not yet been able to clarify whether the persistence or toxicity of PCBs is by original molecules or due to its metabolites (Beyer and Biziuk, 2009). As weathering is natural process, risk assessment studies are based on the standardized procedures adopted for assessment of pollutants at contaminated sites but their effects on human health can only be defined if the route of exposure is known. PCB can accumulate at higher concentration in aquatic organisms i.e., fish, plankton, than in the sediments and particulate matter and consumption of such contaminated food is the main cause of their accumulation in large aquatic organisms and humans (Oluoch-Otiego et al., 2016). The productivity of phytoplankton is also influenced by PCB exposure along with changes in their composition and metabolic reaction. The role of PCBs in air-water exchange through phytoplankton showed that this exchange determined the amount of PCBs that were accumulated in environments which were not directly experiencing PCB contamination (Dachs et al., 2000). This showed that global ecosystem is affected by PCBs pollution (Häder and Gao, 2015). PCBs have low vapor pressure as well as lower solubility in water so they can be transported from contaminated sites to remote areas through water channels, soil weathering, anthropogenic activities, or even migration of birds (Beyer and Biziuk, 2009).

Rapid industrialization has increased the number of sites that has become contaminated with metals and other compounds that has led to various monitoring and remediation studies worldwide. Mexico, Argentina, Brazil, South Korea, China, India, and Pakistan are among the major leather producing countries and they use 80–90% chromium(III) salts in leather processing (Black et al., 2013). Industrial wastewater is often discharged without prior treatment into nearby streams and ponds in under developed countries (Saxena et al., 2016). The chromium slat used is converted to Cr(VI) once dissolve in water. Thus, the wastewater discharged after the tanning process contains high concentration of chromium metal which is harmful for the environment and human health. Many workers are potentially exposed to chromium because of higher concentration in air. High solubility of Cr(VI) also causes ease of permeability through the cell membrane resulting in mutagenicity and carcinogenicity by interacting with proteins, nucleic acids and fatty acid tissues (Ackerley et al., 2004b; Eastmond, 2012). It is also stable at ambient pH and temperature in the aquatic environment and no natural reduction of Cr(VI) occurs, which help it to persist and remain toxic for longer time.

3. Microbial degradation pathways of PCBs

Extensive studies have been conducted for bioremediation of PCBs due to their carcinogenic nature and persistence (Sharma et al., 2017). Different strategies such as biostimulation and/or bioaugmentation which involves the input of nutrients, oxygen and/or PCB-degrading bacteria are also efficient for transformation of PCB congeners (Mrozik and Piotrowska-Seget, 2010). Although, PCBs are resistant to degradation but numerous studies have reported their effective bacterial degradation (Field and Sierra-Alvarez, 2008). Response of bacterial cells to toxic pollutants depends upon the experimental setup and optimized conditions for degradation in enclosed system that can then be applied for adopting any bioremediation strategy at large scale (Katarína et al., 2018).

3.1. Aerobic PCB degradation

Biphenyl transformation to less contaminated compounds follows aerobic degradation and the ability of biphenyl degrading microbes to transform PCB congeners was first described by Ahmed and Focht (1973). Various biphenyl degrading strains have shown that lower chlorinated PCB congeners are easily transformed under aerobic conditions. PCBs congeners having chlorine atom on one aromatic ring are also easily degradable than the compounds having chlorine atoms on both rings (Pieper, 2005; Seeger and Pieper, 2010). PCBs degradation by aerobic processes can occurs in bacteria, birds, mammals and humans, which leads to the formation of various hydroxylated PCBs. The enzymes that are responsible for oxidative degradation of PCBs are: biphenyl dioxygenase (BphA), catalysis the first reaction of biphenyl catabolic pathway and involved in regiospecific of chlorobiphenyl, dihydrodiol dehydrogenase (BphB) that performs the oxidoreductase activity by acting on CH-CH group of donors. 2,3-dihydroxybiphenyl dioxygenase (BphC) is the third enzyme involved in the degradation of chlorobiphenyl by ring cleavage through oxidative route and 2-hydroxyl-6-oxo-6-phenylhexa-2,4-dienoic acid hydrolase (BphD) hydrolyze the C—C bond to produce benzoic acid during degradation of aromatic compounds (Petrić et al., 2011). Many species of bacteria can degrade PCBs and produce benzoate, but further degradation of benzoates follow different metabolic pathways and enzymes under aerobic or anaerobic conditions. Aerobic bacteria further break down the metabolites to non-toxic compounds (Payne et al., 2013).

3.2. Anaerobic PCB dechlorination

PCBs serve as the electron acceptor in anaerobic reductive dechlorination which is an energy yielding process where hydrogen serves as electron donor and water is proton source (Wiegel and Wu, 2000). Highly chlorinated compounds are not degraded under aerobic conditions as the increase in number of chlorine atoms blocks the enzymatic sites of action for bacteria. Increase in number of chlorine atoms decrease the enzymatic action sites for ring cleavage and reduce its bioavailability by accumulation on sediments (Steliga et al., 2020). Anaerobic transformation patterns in sediments have shown that higher PCB congeners were reductively dechlorinated which results in lower chlorinated congeners accumulation. Highly chlorinated congeners are usually degraded by anaerobic process.

Energy produced during cell respiration under anaerobic conditions is gained by bacteria to reduce PCBs and its rate, route and extent of degradation depends upon the amount of electron donors available in the system. Addition of nitrate, sulfate, H_2, bromoethan sulfonic acid, ferric oxyhydroxide, sodium sulfate or individual PCB can act as electron acceptors in anaerobic processes and also helps in bacterial growth (Wiegel and Wu, 2000; Zwiernik et al., 1998). Mono-chlorinated biphenyl, the final product of anaerobic dechlorination, decreased further to dechlorinated hydrocarbon (2H-CB) under aerobic conditions. Many bacterial species have been reported to involve in anaerobic dehalogebtion of PCB compunds namely *Dehalococcoids* sp., *Ochrobactrum* sp., *Parasegetibacter* sp., *Thermithiobacillus* sp., *Phenylobactrum* sp., *Dehalobium chlorocoercia* and *Sphingomonas* sp. (Li et al., 2016; May et al., 2008; Park et al., 2011).

4. Biological metabolisms for Cr(VI) transformation

Cr(VI) resilient microorganisms are comprised of bacteria, algae, fungi, streptomyces and earthworms that can survive in chromium

contaminated sites due to their genetic makeup and production of enzymes for direct removal (El-Naggar et al., 2020). Microbial resistance and reduction of chromium are independent characteristics and these mechanisms differ from group to group. So, Cr(VI) reduction and resistance among microbial species is a shared ability not exclusive to any specific group of microorganisms (Ahemad, 2014). This specific selection can be explained by horizontal gene transfer among microbes as well as concentration of contaminants that are present in the metal polluted sites (Francisco et al., 2002). However, the development of Cr(VI) reduction or resistance among microorganisms depends upon their capability for genetic mutation, adsorption capacity or environmental conditions like available of substrate. Microorganisms having these capabilities are considered for adopting any bioremediation approach on site or in-situ, after isolation under controlled conditions. Heavy metal resistance bacteria also has antibiotic resist potential (Mahmud et al., 2015). It has been observed that distribution of antibiotic resistance genes can also be influenced by metal contamination at a site (Knapp et al., 2017). So it is necessary to consider the multi metals contaminated sites when working on antibiotic resistance as this will further improves the understanding of the relationship between both phenomena (Chen et al., 2019).

Several bacteria can persist in metal-polluted environments by different mechanisms like DNA methylation, adsorption or uptake and metal biotransformation (Pei et al., 2009). Chromate reducers and non-resistant can transform Cr(VI) depending upon the concentration of chromate in an environment. In case of non-resistant species, growth is inhibited at higher concentrations so not well renowned for degrading ability. Examples of Cr(VI) resistant bacteria are *Pseudomonas aeruginosa* (Xu et al., 2009), *Enterobacter cloacae* (Nahar et al., 2015), *Salmonella* (Ghosh et al., 2000), *Bacillus* (Kamala-Kannan and Lee, 2008) and *Acinetobacter* sp. (Pei et al., 2009). So, the microbes with the property of both Cr(VI) resistance and transformation are considered effective in adopting bioremediation strategy (Soni et al., 2013). This resistance of microorganisms is naturally occurring among the species living in metal contaminated sites so proximity of finding the most effective bacterial strains are higher in those areas (Das et al., 2014).

4.1. Biological accumulation and sorption of Cr(VI)

Accumulation and sorption of chromium have been demonstrated as an effectual bioremediation strategy. The main mechanism of chromium sorption involves electrostatic interactions between sorbate and the surface of the sorbent. Being a surface phenomenon, sorption generally increases with an increase in the surface of the sorbent (Salvestrini et al., 2017). Other factors, particularly pH and surface charge of the sorbent, may play a major role in the process (Shi et al., 2009). In which, various plants (including aquatic plants and marine algae) and microorganisms (bacteria, fungi, yeasts, and algae) have been recognized as operative bioabsorbent agents (El-Naggar et al., 2020; Jacob et al., 2018). Various mechanisms have been proposed for microbial biosorption of heavy metals, e.g. transport across the cell membrane, biosorption by cell walls and entrapment in extracellular capsules, precipitation, complexation and oxidation-reduction reactions (Singh et al., 2013). Through removal processes by microorganisms, chromium can be eradicated during three main processes, that is, biotransformation, bioaccumulation and biosorption, the latter is superior to others, with high selectivity depending on the binding capacity of biological materials used as biosorbents (Joutey et al., 2015; Karthik et al., 2017).

The biosorption capacity varies among inactivated and living cells depending upon the detoxification mechanism adopted by bacteria. Use of living or dead microbial cells for biosorption of metals is potentially a cheaper source for bioremediation as compared to use of conventional bio sorbents (Chaudhary et al., 2017). Living microbial cells, however, require additional nutrients for growth and metabolism that can increase the biological and chemical oxygen demand of the medium. They are also more exposed to hazardous effects of metals so selection of the specific microbe is essential to design a remediation study (Khoo and Ting, 2001). On the other hand, dead microbial cells provide the advantage of no additional nutrient requirement and/or toxic effects of the metal ions. So, dead cells require less maintenance and can be regenerated and reused for further experimentation (Kotrba, 2011; Rezaei, 2016; Sen and Dastidar, 2010). The process of bio-elimination by microorganisms is innovative, low-cost and ecologically beneficial (Karthik et al., 2017).

4.2. Cr(VI) biotransformation through enzymes

Enzymatic biotransformation of Cr(VI) by bacterial metabolism occur by catalysis involving soluble cytoplasmic enzymes (Nguema et al., 2014). Common enzymes involved in the transformation process are reductase, DT-diaphorase, cytochrome, oxidoreductases, hydrogenases, iron reductase, flavin reductases, aldehyde oxidase, and quinone reductases (Montes, 2018; Patra et al., 2010). The type of enzymes involved in Cr(VI) reduction depends upon category of bacterial species involved in the bio-transformation like iron and sulfate reducing bacteria will transform Cr(VI) by enzymes that can be dissimilar to those responsible for the transformation of other metals by NADH/NADPH reductases (Kanmani et al. 2012). Chromate acts as the electron acceptor in cytoplasmic or cytosolic reduction processes. Enzymes responsible for Cr(VI) transformation are present in aerobic, anaerobic and facultative bacteria (Cheung and Gu, 2007; Huang et al., 2021). Membrane bound enzymes under anaerobic conditions are responsible for chromate reduction whereas in case of aerobic reduction enzymes are confined as soluble cytosolic proteins. Different reductases (ChrR, YieF, LpDH, etc.) are involved in Cr(VI) transformation by transferring the electrons and production of reactive oxygen species (ROS) (Ackerley et al., 2004a). These enzymes can be the cytoplasm or stuck to the bacterial membrane cells. For bioremediation of metals, soluble enzymes are more suitable than membrane bound as they are more beneficial in developing biocatalysts and adjust well with the environmental conditions (Baldiris et al., 2018). Other than above mentioned details, several research studies have stated the ability of bacterial strains to transform both contaminants individually as shown in Table 1. Fig. 1 is showing the bacterial transformation pathways of lower chlorinated biphenyls and Cr(VI).

5. Environmental conditions affecting PCBs and Cr(VI) biotransformation

Environmental factors impact on growth and metabolic activities of different microorganisms is pronounced. Environmental factors like carbon source, electron donor, electron acceptor, temperature and pH effect the amount and rate of the PCB and Cr(VI) degradation. Optimization of these factors for accelerated degradation is vital role to adopt an effective bioremediation strategy (Joutey et al., 2013a; Wiegel and Wu, 2000).

5.1. pH and temperature

The bio-availability of PCBs depends upon the balance between its solubility and adsorption to carbon based matter and pH plays vital role in this mechanism (Lavandier et al., 2013). Optimum pH of PCB degrading bacteria under aerobic condition was found to be 6.5–8.3, and acidic pH (4.0) would inhibit their growth (Liu, 2004). The biodegradation efficiencies of total PCBs were pH dependent and found to be 33.5, 27.8, 19.6, and 11.3% at pH 4.0, 6.0, 7.0, and 8.0. The biodegradation effect on the individual congener decreased with increasing number of chlorine molecules (Chen et al., 2015). Temperature also has substantial effect on microbial growth and enzymatic activity for breakdown of aromatic compounds (Simcik et al., 1999). The importance of conducting studies at varying temperatures can never be neglected since temperature influences the microbial growth, enzymatic activities as well as

Table 1
Bacterial strains testified for PCBs and Cr(VI) transformation.

Name of species	Isolation source/conditions/medium	Concentration enriched	Reduction percentage	References
PCBs degrading bacterial spp.				
Alcaligenes xylosoxidans *Pseudomonas stutzeri* *Ochrobactrum anthropic* *Pseudomonas veronii*	Soil/anaerobic/DMA medium with biphenyl as carbon source	PCB DELOR 103100 mg L^{-1}	*Alcaligenes xylosoxidans* 55–60% *Pseudomonas stutzeri 45–45%* *Ochrobactrum anthropic* 35–40% *Pseudomonas veronii* 30–45%	(Murínová et al., 2014)
Pseudomonas alcaliphila *Pseudomonas plecoglossicida* *Ochrobactrum anthropic*	Soil/aerobic & anaerobic Plant-microbe interaction/mineral mediums with biphenyl as carbon source	107.9 mg L^{-1} ± 14.1	*Pseudomonas alcaliphila* 37.6% in nightshade & 32% in tobacco *Pseudomonas plecoglossicida* 21.7% in nightshade & 52.8 in tobacco *Ochrobactrum anthropic* 46.7% in nightshade & 24.7% in tobacco	(Kurzawova et al., 2012)
Rhizobium meliloti (*Rhizobium*)	Liquid/aerobic/LB & HM minimal medium/biphenyl as carbon source	PCB 1242 100 mg L^{-1}	Degradation upto 5 chlorine atoms was 26–40%	(Damaj and Ahmad, 1996)
Sinorhizobium meliloti (GM *Rhizobium* strain)	Soil microcosms/anaerobic/YMA & YMB/biphenyl	40 mg L^{-1} of 21 PCBs mixture	10% inocula 5.4% to 59.8% 20% inocula 11.8% to 62.3% for all 21 PCBs	(Tu et al., 2011)
Burkholderia xenovorans *Cupriavidus necator* *Pseudomonas pseudoalcaligenes*	Liquid culture/anaerobic/LB medium/biphenyl	PCB Aroclor 1242 1000 mg L^{-1}	Consortium 80–100% in for di, tri and tetra chloro PCB congeners	(Wittich et al., 2013)
Cr(VI) reducing bacterial spp.				
Bacillus subtilis	Liquid/aerobic/minimal medium–trisodium citrate and dehydrate glucose	0.1 to 1 mM	100%	(Garbisu et al., 1998)
Pseudomonas putida	Liquid/anaerobic/Luria-Bertani-citric acid-Tris-acetic acid/MSM	1 mM	100%	(Park et al., 2000)
Shewanella alga	Liquid/aerobic-anaerobic/M9, TSB, BBHIB broth	4.836,10, 37.125, 260 mg L^{-1}	100% reduction of lower concertation in 2 days in all three medium More than 10 days for complete reduction at 260 mg L^{-1}	(Guha et al., 2001)
Klebsiella pneumoniae *Mangrovibacter yixingensis*	Tannery/aerobic/BHIB	20, 40, 60, 80 and 100 mg L^{-1}	Tolerant to 100 mg L^{-1} Cr(VI)	(Sanjay et al., 2020)
Arthrobacter sp. SUK 1201 *Arthrobacter* sp. SUK 1205 *Pseudomonas putida* *Corynebacterium paurometabolum*	Chromate mine/aerobic/PYEG	50–800 μM	100% in 48 h at 100 μM Decrease with increasing concertation	(Dey et al., 2014)
Providencia sp.	Soil-liquid/aerobic-anaerobic/Luria broth (tryptone-yeast extract)	100–400 mg L^{-1}	100%	(Thacker et al., 2006)
Achromobacter sp.	Industrial site/anaerobic/Luria Broth; glucose-lactate	2–8 mM	100% in 150 min for highest concentration	(Zhu et al., 2008)
Ochrobactrum sp.	Dying industry/aerobic/glucose	100–1500 μg mL^{-1}	100% reduction at 200–721 μg mL^{-1} in 72–96 h	(Sultan and Hasnain, 2007)
Serratia proteamaculans	Cr contaminated/anaerobic/MS medium	100–400 mg L^{-1}	100% for 100 mg L^{-1} decrease to 15% for 400 mg L^{-1}	(Joutey et al., 2014)

bioavailability of PCBs (Wiegel and Wu, 2000). Fluctuation in day and night temperature can affect different microbes under natural conditions, then those studied under controlled conditions.

Temperature and pH significantly affect growth and metabolic activities of Cr(VI) reducing bacteria (Kanmani et al. 2012). *E. coli* and *Enterobacter cloacae* has varied temperature range (10–50 °C) for Cr(VI) reduction while optimum temperature of 36 °C and 30 °C is most suitable. Between the pH range of 6–10 and 1000 μg mL^{-1} Cr(VI) concentration, *Bacillus cereus* achieved maximum reduction (72%) at pH 8.0 while only 60–70% reduction was observed with other conditions (Singh et al., 2013). Temperature of 30–37 °C is reported optimum for Cr(VI) transformation (Cheung and Gu, 2007) whereas enzymatic studies for Cr(VI) reduction showed that Cr reductase enzyme had an activity maximum in the 25–37 °C temperature range and 7 pH (Xiao et al., 2008). Cr(VI) transformation is most efficient under acidic conditions as higher pH values enhance chromium removal but neutral pH is still the most affective in supporting the bacterial growth (Silva et al., 2009). *Clostridium* sp. isolated form activated sludge was studied for chromium resistance and detoxification of 50 mg L^{-1} Cr(VI) concentration. At pH 7 maximum reduction was noticed with 30 °C temperature at maximum concertation of 40 mg L^{-1} after which reduction rate decreases under aerobic conditions (Nguema and Luo, 2012).

5.2. Carbon sources/co-substrate

Carbon substrates plays significant role in transformation of recalcitrant compounds as they can provide the necessity for survival of microorganisms (Kumar and Gopal, 2015). Different organic and plant mediated metabolites seems to effect PCB dechlorination depending upon prevailing conditions. Co-metabolism is the major condition for PCB degradation mostly, as soil microbes cannot use it as growth substrate. Under anaerobic conditions however, higher chlorinated PCBs act as electron acceptors as they are highly oxidized and undergo reductive dechlorination (Vasilyeva and Strijakova, 2007). Acetate, propionate, butyrate and hexanoic acid have been shown to be available in nutrient limited organic soils, whereas glucose, acetate, methanol etc. are mostly available in organic rich soils (Wiegel and Wu, 2000). Various inducers are also proposed to enhance the degradation capability of bacteria. Biphenyl is frequently used as inducer and growth substrate due to their structural resemblance to PCB congeners (Luo et al., 2007; Pham et al., 2015). Ease of availability and utilization of glucose makes it an efficient carbon source for most microorganisms.

Biphenyl is a naturally occurring compound and many bacterial species have enzymes required to break bonds of one of the benzene rings thus destabilizing the compound for further degradation. Studies have

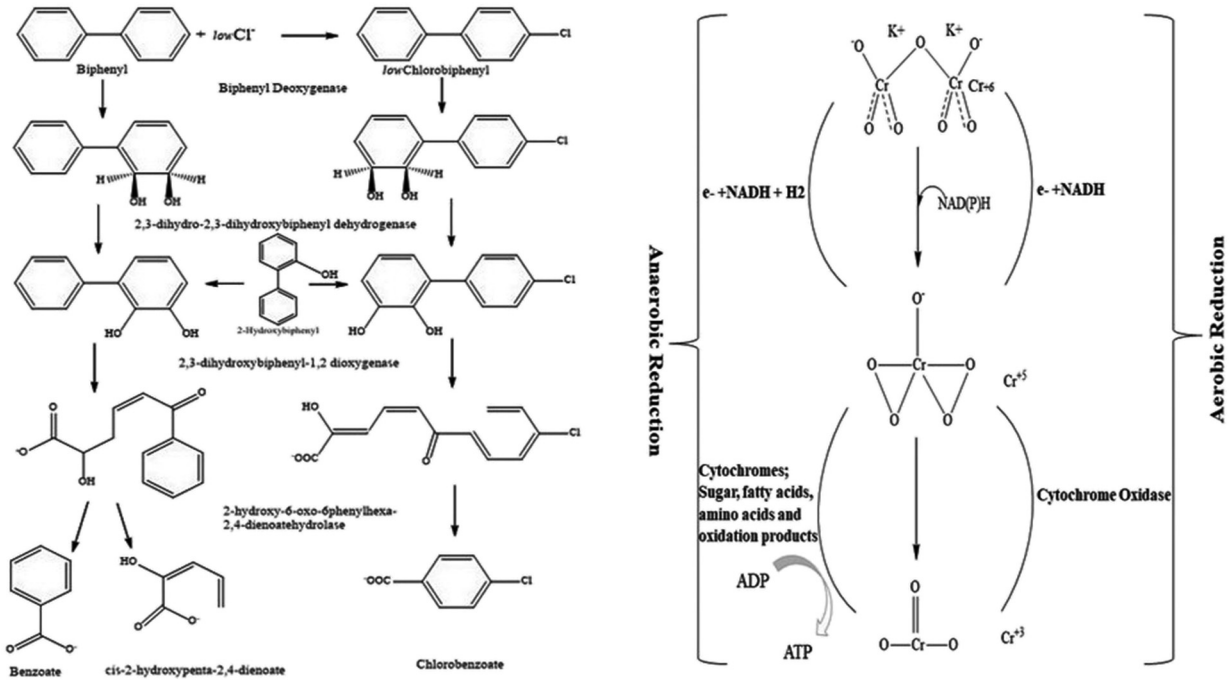

Fig. 1. Dissipating the biphenyl dioxygenase pathway for reduction for biphenyl and lower-chlorinated biphenyl under aerobic conditions (left). As similar enzymes are responsible to degrade biphenyl and lower-chlorinated biphenyl into different intermediate by products, figure is presenting biphenyl dioxygenase pathway for both contaminants in single frame. Aerobic and anaerobic reduction pathway of Cr(VI) involving cytochrome oxidase and cytochrome respectively (right) with the production of sugar, fatty acids, amino acids, and conversion of ADP into ATP.

shown that biphenyl in addition to serving as an enrichment substrate can also be a co-metabolite that can enhance the rate of dechlorination (Vergani et al., 2017). Under anaerobic conditions, PCBs are reduced to lower chlorinated compounds through reductive dehalogenation, but biphenyl structure is not broken down. Under aerobic conditions, lower chlorinated compounds are detoxified along with breakdown of biphenyl structure (Garrido-Sanz et al., 2018). One problem with using biphenyl as a field enrichment compound is that biphenyl is toxic and cannot be released into the environment (Selesi and Meckenstock, 2009). This has led to thoughts about alternative compounds such as aromatic flavenoids and terpenes produced naturally by many plant species (Aken et al. 2009). Flavenoids plays their role in plant and fruit pigmentation which helps in attracting pollination organisms. Bioaugmentation and bio stimulation strategies were adopted for the degradation of long term contaminated PCB site with two isolates *Achromobacter xylosoxidans* and *Stenotrophomonas maltophilia* using ivy leaves (Dudášová et al., 2016). The highest bioaugmentation potential was shown by *Achromobacter* sp. *Ochrobactrum* sp. and *Rhodococcus* sp., since they showed faster growth on biphenyl and PCB used as sole carbon source (Dudášová et al., 2014). Priming with PCBs can enhanced their degradation as the organisms involved in the reaction grow better but it largely depends upon environmental factors and electron availability (Field and Sierra-Alvarez, 2007).

Several studies were designed on microbial reduction of Cr(VI) but only few studies have been conducted on carbon source effects among microbial communities responsible for Cr(VI) transformation (Desai et al., 2008). Using sodium acetate and sucrose as carbons sources for Cr(VI) transformation in batch reactors at concentration of 6, 13, 30 and 115 mg L^{-1} showed that reduction increased by 1.3–2.1 folds. Microbial community analysis showed that presence of multiple species from i.e., *Actinobacter* sp., *Defluvibacter* sp., *Psedoxanthomonas* sp. (Tekerlekopoulou et al., 2010). Scientists have described that Cr(VI) reducing ability of microbes is significantly affected by use of different carbon sources (Baldiris et al., 2018). Different types of carbon sources i.e., lactose, glucose, citrate, cheese whey and acetate, acting as electron donor in batch reactor @ 25 mg L^{-1} Cr(VI) concentration, suggested cheese whey as most effective of Cr(VI) transformation (Orozco et al., 2010).

5.3. PCBs and Cr(VI) concentration

Heavy metals and organic compounds concertation influences the composition of soil microbial groups (Sobolev and Begonia, 2008; Tang et al., 2014). Mixture of pollutants can adversely affect the microbial diversity and enzyme activity of soils under higher levels of contamination (Thavamani et al., 2012). For PCBs dechlorination, an observed concentration at contaminated site may vary from several hundreds to 1000 ppm. Increased adsorption of PCBs on mineral compartments of soil may decrease dechlorination process if the concentration of PCB is low (Lehtinen, 2010). Low concentrations of PCBs also affect the degradation process as microbial activity may not even start (Borja et al., 2005).

Bacteria residing in contaminated soil or water can tolerate toxicity posed by Cr(VI) (Thatheyus and Ramya, 2016). *Bacillus coagulans* uses soluble enzymes for Cr(VI) transformation in company of malate (0.8 g L^{-1} concentration) as electron donor. *Bacillus coagulans* was able to degrade 32 Cr(VI) and tolerated 512 mg L^{-1} concentration within 72 h. Increasing the toxicity of the medium, decreased the reduction rate in combination with lead at 128 mg L^{-1} (Belapurkar et al., 2016). Bacterial genera such as *Aeromonas*, *Mycobacterium*, *Corynebacterium* and *Bacillus* also contained biodegradative pathways with regards to chromium (Mrozik et al., 2003). Cr(VI) transformation by *Bacillus sp.* KSUCr5 was noticed at 10–300 mg L^{-1} concentration. The bacterial strains rapidly reduced 40 mg L^{-1} Cr(VI) in 24 h whereas 80–100 mg L^{-1} concentration was totally removed in 48–72 h. At higher concentration (150–300 mg L^{-1}), however, reduction ability significantly decrease to 44% with more time to achieve reduction (Ibrahim et al., 2011). Tannery effluents have been reported to contain multiple pollutants including Cr(VI) and PCBs (Korpe et al., 2019; Tadesse et al., 2017).

5.4. Metal ions and electron complexes

Role of metal ions and electron complexes on PCBs degradation have not clearly been understood. Role of metal ions in microbial activity inhibition including dehalogenation and reductive dechlorination is predominant factor in adopting to a bioremediation strategy. However, the role of metal ions on microbial degradation of organic contaminants has not clearly been studied. The only studies present till date are related to organic contaminants degradation in presence of metal ions (Sandrin and Maier, 2003). A PCB degrading and metal tolerant specie, *Pseudomonas pseudoalcaligenes* KF707 can effectively detoxify both under optimized conditions even the toxicity level is high (Tremaroli et al., 2010). For effective dehalogenation, different studies have discussed the critical role of dehalorespiration and dissimilatory iron reduction (Li et al., 2008). In dehalorespiration, halogen-free compounds and halogenated congeners are accumulated as halogenated compounds and play the role of electron acceptors (Hiraishi, 2008).

Electron shuttles play a vital part in transformation of Cr(VI) and activities of microbes. In absence of oxygen, Cr(VI) act as electron acceptor for large number of electron donors which includes fats, hydrogen, carbohydrates, and proteins (Joutey et al., 2015). Presence of metal ions in tannery effluents, due to extensive manufacturing processes and involvement of different chemicals, can affect the treatment processes negatively (Shah, 2014; Tariq et al., 2006). The interference of trace metals, with the proteins or enzymes involved in the redox reaction, form strong complex with the protein molecules and helps in reduction or completes detoxification of pollutant by deactivating the enzyme activity (Jadhav et al., 2012). Trace metals, under anaerobic conditions, act as electron acceptor, but they are not soluble at neutral pH thus affecting the transfer of electron needed for bacterial growth. Organic compounds on the other hand can act as electron shuttling compounds and fast-track the electron transmission from a primary donor to acceptor (Joutey et al., 2013b; Leewis et al., 2016).

Role of electron shuttles and metallic ions in simultaneous detoxification of azo dye and Cr(VI) was observed using *Pseudomonas putida* in tannery effluent. Mineral salts medium was enriched with Cr(VI) (2 mg L^{-1}) concentration and azo dyes (100 mg L^{-1}). The percentage biotransformation for simultaneous removal was increased from 68% to 96% with the inclusion of electron shuttles hydroquinone and uric acid as electron shuttles at 1 mM concentration. 100% dye and 97% Cr (VI) was removed in 12–18 h, whereas other organic compounds i.e., mannitol, EDTA and sodium benzoate inhibits the simultaneous biotransformation of both contaminants (Mahmood et al., 2015a). Soil enrichment studies evaluated the correlation between electron donors and Cr(VI) reduction. Glucose addition with formate and hydrogen as electron donors increased the bioavailable hydrogen and augmented Cr(VI) transformation in soils in comparison to acetate, benzoate and lactate (Marsh and McInerney 2001).

6. Simultaneous approaches for biotransformation of Cr(VI) and PCBs

Co-existence of metal ions and organic compounds in industrial effluent stimulated the idea for simultaneous treatment as a viable option especially for the developing countries where treatment systems are not properly installed. Previously no studies are reported for the simultaneous detoxification of both contaminants. Various bacterial species can degrade the both PCBs and chromium individually. So simultaneous bioremediation strategy for removal of multi contaminants form industrial effluents can be eco and cost friendly technique.

Individual and simultaneous treatment of phenol and chromium by two indigenous bacterial strains, *Pseudomonas putida* and *Escherichia coli,* respectively under optimized conditions (30 °C temperature, pH 7) suggested that *Pseudomonas putida* effectively degrades a maximum 1000 mg L^{-1} phenol in 72 h and *Escherichia coli* degrades a maximum 40 mg L^{-1} Cr(VI) in 42 h individually (Debadatta and Susmita, 2012). For simultaneous degradation of both Cr(VI) at 5, 10, and 15 mg L^{-1} and phenol at 500 and 750 mg L^{-1} concentration using the co-culture of microorganisms was studied. Both strains can efficiently reduce the contaminants to acceptable limits. Cr(VI) and phenol detoxification of was also observed with *Bacillus* sp. and *Pseudomonas putida* under optimized conditions simultaneously (Liu et al., 2008). *Bacillus* sp. utilized the degradation products of phenol as source of energy and electron donors in reducing Cr(VI). Significant Cr(VI) (15 mg L^{-1}) transformation was observed at 150 mg L^{-1} concertation of phenol and it was noticed that phenol degradation was higher than Cr(VI) reduction but it was independent of the *Bacillus* sp. cell content.

Lactobacillus paracase, native to sea sediments of North Atlantic, was capable of reducing Cr(VI) and black dye instantaneously. Under optimum aerobic conditions of pH (5–7), temperature (25–30 °C) and salt concentration (0–60%) NaCl, *Lactobacillus paracase* reduced 95.8% of Cr (VI) and degraded 92.3% of dye at initial concentration of 100 mg L^{-1}, individually. Simultaneously, detoxification ability of the strain was reduced to 58.5% Cr(VI) and 51.9% dye, respectively (Huang et al., 2015). Another study used *Brevibacterium casei*, isolated form sewage sludge samples of dye industry, for simultaneous transformation of different dye acid orange 7 and Cr(VI), under the optimal conditions (3.0 g L^{-1} $(NH_4)_2SO_4$, 0.24 g L^{-1} glucose, and 0.2 g L^{-1} peptone) with pH 7 at 35 °C temperature, suggested maximum transformation, 83.4% and 40.7% of Cr(VI) and dye respectively (Ng et al., 2010). Pentachlorophenol (PCP) and Cr(VI) were simultaneously treated with strains isolated from treated tannery effluent (Tripathi and Garg, 2013).

Simultaneous bioremediation of Cr(VI) with chloro-organics and decolorization of dyes was observed with native *Bacillus cereus* isolate in tannery effluents (Tripathi and Garg, 2014). The samples were distributed into diluted (3:1) and undiluted concentrations. Upon microbial treatment, dechlorination, decolorization and Cr(VI) remediation was substantial in diluted samples. Maximum microbial growth, dechlorination, decolorization and Cr(VI) bioremediation was attained at 8.1 pH within 72 h. The results indicated 42.5% decolorization, 74.1% dechlorination and 34.2% Cr(VI) remediation which improves in bioreactor by 3.3 to 7.5% Cr(VI) reduction. Co-culture of immobilized *Bacillus cereus* isolate and *Pseudomonas putida* enhanced Cr(VI) remediation by 10.2% under lab conditions.

Biodegradation of PCBs is very complex due to various physicochemical factors involved. They are particularly transformed through reductive dechlorination under the action of different microorganisms (Wu et al., 2002). Relative proportion of some congeners increased or decreased through microbial metabolism. It has been observed that the lower-CBs compounds are easily volatilized and biodegrades as well as more soluble in water whereas, highly-CBs are more resistant to degradation, volatilization along with high sorption affinity to soils and sediments (Beyer and Biziuk, 2009). The complex nature of higher chlorinated and less polychlorinated biphenyl degradation under anaerobic and aerobic conditions have induced several characteristics that are similar in reduction of metal ions. As PCBs are two rings attached to each other so initial process in case of monochlorinated biphenyl is reduction which is comparable to that of heavy metals. It is also interesting to that there are similar bacterial species that can reduce Cr(VI) and degrade PCBs individually in separate studies. *Pseudomonas aeruginosa* was found suitable for simultaneous biotransformation of Cr(VI) and phenol (Song et al., 2009). In another study *Pseudomonas aeruginosa* was also able to degrade 1.0 μg mL^{-1} concentration of PCB Aroclor 1260 in 96 h (Mathews and Sithebe, 2018). Similarly, *Stenotrophomonas maltophilia* (Baldiris et al., 2018; Dudášová et al., 2016; Somaraja and Gayathri, 2016), *Pseudomonas* sp. (Hirose et al., 2019; Wani et al., 2019) and *Bacillus* sp. (Li et al., 2020; Sun et al., 2018) have been reported to bio transform both contaminants individually in separate studies. Due to reduction similarity and co-existence of both contaminants under alike environmental conditions, simultaneous approach may give a new understanding in microbial metabolism for recalcitrant

Table 2
Different bioreactor systems adopted for transformation of Cr(VI) and PCBs.

Bacterial species	Bioreactor	Concentration used	Removal percentage	Reference
Cr(VI)				
Bacillus megaterium-ASNF3	Soil bioreactor	1000 mg L^{-1}	86% in 60 days	(Aslam et al., 2016)
Bacillus sp.	Packed-bed bioreactor	10–200 mg L^{-1}	100%	(Chirwa and Wang, 1997)
Bacillus drentesis *Bacillus thuringiensis* *Enterobacter* sp. *Lysinibacilus sphaericus*	Packed-column microcosm reactors	40 mg L^{-1}	Almost 100%	(Molokwane and Nkhalambayausi-Chirwa, 2009)
Consortium (*Proteobacteria*, *Actinobacteria*, *Firmicutes*)	Anaerobic sludge bed reactor	50 mg L^{-1}	90% in 70 days	(Qian et al., 2016)
Consortium (*Cyanobacteria*, *Proteobacteria*, *Bacteroidetes*)	Plant microbe fuel cell bioreactor	19 mg L^{-1}	99% in 250 h	(Habibul et al., 2016)
Pseudomonas putida (Simultaneous Azo Dyes + Cr (VI)	Biochar packed bioreactor	2–10 mg L^{-1}	98% 24 h	(Mahmood et al., 2015b)
Consortium (*A. junii*, *E. coli*, *B. subtilis*)	Packed bed bioreactor	100 mg L^{-1}	24%	(Samuel et al., 2013)
Bacillus sp.	Packed bed bioreactor	300 mg L^{-1}	100%	(Kathiravan et al., 2010)
Acinetobacter haemolyticus	ChromeBac system	81 mg L^{-1}	100% in 10 days	(Ahmad et al., 2010; Wan et al., 2010)
PCBs				
Consortium	Moving-bed biofilm reactor	PCB77 0–8 μg L^{-1}	73% anaerobic 84.4% aerobic in 7 h	(Dong et al., 2015)
Rodococcus, *Pseudoxanthomonas*, *Agromycess* and *Pseudomonas*	Sequencing biofilm reactor	PCB 1242 PCB 1254 with 3 μg L^{-1}	99% in 250 days	(Teimouri et al., 2015)
Burkholderia xenovorans LB400	Biphasic bioreactors	Aroclor 1242 30 μg L^{-1}	90% in 120 h	(Rehmann and Daugulis, 2008)
Rhodococcus spp., *Pseudomonas* spp., *Pseudoxanthomonas* spp.	Aerobic sequencing batch biofilm reactor	20–700 μg L^{-1}	92–99%	(Nabavi et al., 2013)

compounds. Table 2 exhibiting various bioreactors system used for Cr(VI) reduction and PCBs degradation under different conditions.

7. Bioaugmentation strategies for biotransformation of Cr(VI) and PCBs

Bioaugmentation, the addition of pollutant degrading microbes into the water treatment system, is an efficient method for the removal of organic compounds and metal ions with and without oxygen (Nzila et al., 2016). The perspective of using consortia of microorganism that degrade different pollutants is the best possible solution to adopt for simultaneous treatment of all the pollutants in a single system (Providenti et al., 1993). Application of bioremediation strategy through bioaugmentation and potential of microbes involve in the system are key factors for the degradation of pollutants (Tyagi et al., 2011). Couple of strategies that are involved in application of bioaugmentation strategy are through bioreactors and biofilm covered material as vehicle delivery system for remediation. Earlier is lot more mechanical and used previously at many remediation approaches whereas later is fairly a new concept in adoption for biodegradation. Effectiveness of both bioremediation strategies depend upon biofilm growth and adhesiveness, environmental factors, and engineering structure for reducing the metals and organic pollutants at the application site (Asri et al., 2018).

Toxic effects of Cr(VI) have been minimized using membrane bioreactors and helped in the reduction to less toxic chromium using agar–agar films immobilized cells of *Pseudomonas* (Konovalova et al., 2003). A continuous H_2 fed fixed bioreactor was developed for the reduction of chromium and sulfate starvation, inoculated with bacterial consortium of *Desulfomicrobium norvegicum* (Battaglia-Brunet et al., 2007). Presence of sulfate in feed stock increased the chromate reduction whereas chromate reduction decreases in absence at 500 mg L^{-1} concertation in absence of sulfate feedstock. *Cellulomonas* sp. was observed in columns fixed bioreactor. The analysis of effluents showed that iron was continuously spotted in the effluent Fe (III) form and was reduced into Fe (II) form, which resulted in protracted abiotic reduction of Cr(VI). The study suggested that *Cellulomonas* sp. formed a penetrable reactive barricades to reduce Cr(VI) and Fe (III) even if electron donors are absent (Viamajala et al., 2008).

Biofilm covered activated carbon particles are efficient in removing organic pollutants form wastewater treatment system as they are not only absorbing the pollutants form the environment, degrading them and making them unavailable to be suspended in the soil and aquatic system. Use of bacterial biofilm, grown on activated carbon, has widely been used in wastewater cleaning, potable water purification, and removal of organic contaminants. Previously, aerobic granular biofilms have been observed to remove metallic compounds through biosorption. So, biofilm-based Cr(VI) reduction can be an efficient bioremediation strategy as the biofilm bound cells are highly resistant to increasing concentrations and allow easy separation of microbial biomass form water (Nancharaiah et al., 2010). Treatment of PCBs contaminated sediments with granular activated carbon (GAC) demonstrated 62% degradation of PCBs by a GAC column (Jing et al., 2018). Bioaugmentation of PCBs in liquid phase using biofilm covered material as vehicle delivery system serves dual purpose i.e., accumulation of organic compounds into the surface along with degradation through microbes. So, simultaneously PCBs degrading *Burkholderia xenovorans* LB400 and DF1 biofilms were grown on a 3% activated carbon material under aerobic and anaerobic condition respectively (Kjellerup and Edwards, 2013). Grown biofilms covered activated carbon material were transferred to sediment medium with 50 ppm concentration of A1248 in a mesocosm study and samples were taken after 0,28, 60, 80, 135, 160 and 200 days. Results suggested that dichlorination was less extensive with anaerobically grown DF1 as compared to aerobic grown *Burkholderia xenovorans* LB400. Simultaneous biotreatment of multiple contaminant sites can be achieved using any possible bioremediation strategy which can have dual purpose approach of adsorption and degradation at same time. Fig. 2 illustrates the possible mechanism for simultaneous transformation of PCBs and Cr(VI). Cr(VI), act as an electron acceptor in transformation to lower forms and lower-chlorinated PCB congeners can serve as electron donors for many bacteria under aerobic conditions. Therefore, with the occurrence of an electron donor and accepter in single medium, reduction of Cr(VI)

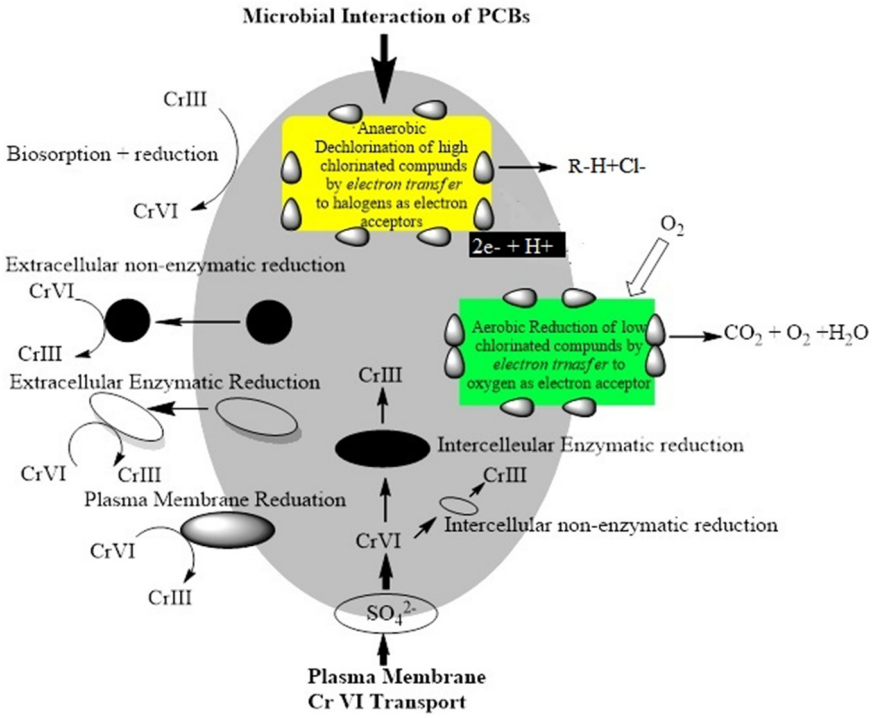

Fig. 2. Possible mechanism for simultaneous degradation of both Cr(VI) and PCBs contaminants in one system. Cr(VI) acts as electron acceptor in reduction to Cr III and aerobically as growth substrates, lower-chlorinated congeners can serve as electron donors (energy sources) for many bacteria. The quantity of Cr(VI) in bacterial culture reduces may be due to immobilization of Cr(VI) and reduced by the enzymatic reaction inside the bacteria. When Cr(VI) is reduced to Cr III, oxygen atoms are released which can/may be utilized for oxidation of mono-chlorinated biphenyls to degraded by-products. The assumption that reduced Cr III will get oxidized to Cr(VI) again in aerobic conditions remains unclear as that oxygen might have been used for the oxidation of mono-chlorinated biphenyls.

along with oxidation of mono-chlorinated biphenyl is possible. This potential solution needs further evaluation in a simultaneous bioremediation system of metals and organic compounds. Secondly, Cr(VI) can become immobilized by bacterial species followed by enzymatic reduction. When Cr(VI) is reduced, oxygen is released, which may be utilized for oxidation of mono-chlorinated biphenyls. It was noticed that Cr(VI) is readily transformed in three–five days, whereas degradation of mono-chlorinated biphenyls can take weeks. Whether reduced Cr(III) will become oxidized to Cr(VI) again under aerobic conditions remains unclear as oxygen might have been utilized for the oxidation of mono-chlorinated biphenyls and other easily degradable organic compounds. Thus, a competition for the utilization of oxygen in a single system is occurring, which may lead to less or no oxygen in system for dissolved chromium oxidation. Subsequently, the first step for transformation of Cr(VI) and PCBs is the reduction, it is therefore possible that the resilient bacteria can metabolize both contaminants simultaneously. As the bacterial transformation of both contaminants is mostly dependent upon presence of specific enzymes and functional genes, further research regarding the genetic changes and horizontal gene transfer in microorganisms having resistance to multiple contaminants can be an interesting study. Also, effects of multi-contaminated sites on microbial community structure of soil/sediments along with role of changing climate on microorganisms involved in bioremediation especially those having resistance to metals and organic compounds must be studied.

8. Future challenges

Water scarcity is a concern in developing countries due to an increase in population, diminishing natural resources and increased per capita water use. Rapid urbanization and industrial developments demand large amount of clean water for meeting these needs. Industrial processes lead to production of a large amount of wastewater discharged into the environment, which is unsafe for use due to presence of pollutants and contaminants. Reuse of wastewater for irrigation and domestic purposes through efficient wastewater treatments systems is a widespread practice in developed countries. Resource constraints, poor management and policy issues are often obstacles in the development of such wastewater treatment facilities in under develop countries. An industrial shift from developed to developing countries in the last few decades has increased the calamity of this issue and proper remediation strategies are required. Adapting to a biologically friendly and cost-effective remediation strategy to treat polluted water is essential not only for human health and food security but also for future clean development programs. Research findings presented above regarding the microbial transformation of Cr(VI) and PCBs in water and soil systems are among the different adopted strategies that can be progressive for the quality of life and ensure food security long-term. Bacterial assisted phytoremediation, sorption-desorption studies, degradation of metabolites and enzymatic studies need more focus for adopting a bioremediation strategy. A large amount of work has been conducted and published for individual microbial treatment and enzymatic transformation of both contaminants individually, but a simultaneous approach has never been adopted. It is interesting to note that sources and presence of both pollutants might be different, but many industrial areas in developing countries are mixed with many types of industries at one place with a single outlet and drainage system. So, a bioremediation approach effective in addressing the multi contaminated site with various types of indigenous bacteria working together can be much useful in resource constraint countries.

9. Conclusion

The paper reviewed the sources of Cr(VI) and PCBs in the environment, their toxicity to the biotic components, bacterial

mechanism for biotransformation of both contaminants individually and simultaneous biotreatment potential for both contaminants. Complexity of PCB compounds and their chemical and physical properties effects its transport and fate in environment. This ultimately effects the choice to select appropriate remediation approaches. On the other hand, multi-purpose application of Cr(VI) has made it one of the most common pollutant in industrial wastewater. Biotransformation of both contaminants is dependent upon the environmental factors like pH, temperature, redox conditions, carbon and nitrogen source and concentration in the medium. Individual bioremediation of both Cr(VI) and PCBs by bacterial strains have been discussed in the paper with example of species which can degrade both contaminants in separate studies. This is the focus of this review paper and possible mechanism for simultaneous biotreatment has been explained. Evaluation of simultaneous biotreatment potential still needed more work for enzymatic and metabolic reactions and that also depends upon the type of bioremediation strategy adopted at any site. Bioreactors and biofilm covered materials are proven and sustainable treatment solutions, but successful treatment not only depends on the appropriate selection of the most effective remediation technology, it is also needs to consider the environmental and human health impacts as well as cost effectiveness. The findings in this review suggest that there is a possibility of transforming both hexavalent chromium and polychlorinated biphenyl under a sequential aerobic-anaerobic bioremediation system and it is a suitable technology for the treatment of both contaminants simultaneously. Therefore, a simultaneous approach would be beneficial and effective for co-removal of such metals and organic compounds in one system.

Declaration of competing interest

The authors confirm that there are no known conflicts of interest associated with this manuscript and there has been no significant financial support for this work that could have influenced its outcome.

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