*BIOSCIENCES BIOTECHNOLOGY RESEARCH ASIA*, March 2019. Vol. **16**(1), p. 01-13

# A Review on *in vitro* and *in vivo* Bioremediation Potential of Environmental and Probiotic Species of *Bacillus* and other Probiotic Microorganisms for Two Heavy Metals, Cadmium and Nickel

**Pragya Goyal[1], Pranoti Belapurkar[2]* and Anand Kar[3]**

[1]Department of Biotechnology, IPS Academy, Indore, Madhya Pradesh, India.
[2]Department of Biosciences, AIMSR, Mangliya, Indore, Madhya Pradesh, India.
[3]School of Life Sciences, Devi AhilyaVishwavidyalaya, Indore, Madhya Pradesh, India.

http://dx.doi.org/10.13005/bbra/2714

(Received: 28 January 2019; accepted: 28 March 2019)

**Microbial assisted remediation is the ray of hope in the current scenario of tremendous heavy metal pollution. The indiscriminate release of heavy metal laden industrial effluents in the water bodies and soil is now manifesting itself in the form of life threatening health hazards to humans. The conventional heavy metal remediation strategies are not only expensive but are ineffective in low metal concentrations. Microbial assisted remediation of heavy metals has come forward as the cheap and easy alternative. Amongst the various bacterial genera actively involved in bioremediation of cadmium and nickel in the environment, genus *Bacillus* has shown remarkable ability in this respect owing to its various biochemical and genetic pathways. It can perform bioremediation using multiple mechanisms including biosorption and bioaccumulation. This genus has also been able to reduce toxicity caused by cadmium and nickel in eukaryotic cell lines and in mice, a property also found in probiotic genera like *Lactobacillus* and *Bifidobacterium*. This paper reviews the role of environmentally present and known probiotic species of genus *Bacillus* along with different probiotic genera for their various mechanisms involved for remediation of cadmium and nickel.**

**Keywords**: *Bacillus,* bioremediation, cadmium, nickel, probiotic.

Humans have been using various metals for their day-to-day activities for a very long time. However, it was the industrial revolution which caused the heavy metal contamination of water bodies and soil. This problem has been compounded by rapid urbanization and industrialization. Other sources of heavy metals such as nickel, chromium, cadmium, mercury, arsenic and lead include natural environmental causes like volcanic eruptions and agricultural residues (He *et al*., 2005). Their concentration is found highest at their point sources, i.e. all metal based industrial operations (Fergusson, 1990; Bradl, 2005; He *et al*., 2005). The presence of heavy metals is a cause of concern as they are highly toxic, non- biodegradable and have exceptionally long half-lives (Aiking *et al*., 1984). These heavy metals enter the food chain and reach top level by bioconcentration, bioaccumulation and biomagnification phenomena, thereby affecting the human health adversely (Ahmed *et al*., 2017). Their deleterious effects are found in both adults and children, and include

*Corresponding author E-mail: pranotibelapurkar@acropolis.in

disorders of heart, kidneys, reproductive system, nervous system and skeletal system(Jaishankar *et al*., 2014).In extreme cases,may also cause death.

Currently, the cause of worry is the fact that conventional technologies for removal of heavy metals from environment such as chemical precipitation, electrochemical treatment and ion exchange are not only proving expensive but are also not useful if the heavy metal concentration is low. The alternative technology to this is bioremediation which is proving beneficial due to its low cost of running and maintenance and ease of operation (Chaney *et al*., 1997; Chang *et al*., 1997; Chaney *et al*., 2000; Borma *et al*., 2003; Borrok *et al*., 2004). Overtime, microbes have developed different mechanisms to survive and tolerate heavy metals found in soil sediments and aquatic ecosystems. These mechanisms include bioaccumulation, biotransformation and biosorption amongst various other approaches. The predominant bacterial genera identified for bioremediation of heavy metals by various biochemical and genetic pathways are *Bacillus*, *Pseudomonas* and *Enterobacter* (Table 1). These microbes present to us important means of reducing heavy metal concentration and thus their toxicity in the environment.

In recent times microbiologists have reported that probiotic microorganisms like *Lactobacillus* sp. have the ability to detoxify heavy metals *in vitro* and *in vivo* (Table 2). This led to search for species of other bacterial genera having similar capacity. Genus *Bacillus* fits this criterion as some of its species have shown excellent heavy metal bioremediation potential in environment while others have exhibited probiotic property along with the ability to reduce heavy metal concentration *in vitro* as well as *in vivo* (Table 2). This review focuses on bioremediation of nickel and cadmium by *Bacillus* sp. and probiotic bacterial species.

**Cadmium [Cd (II)]**

**Toxicity of cadmium**

Cadmium is a naturally occurring element existing in earth's crust that is generally complexed with zinc or lead compounds (Hans Wedepohl, 1995). Commercially, it is used in the production of TV screens, batteries, paints, alloys etc. Industry workers are continually exposed to high levels of cadmium where it enters their body both by inhalation and ingestion (Nordberg *et al*., 2007). The effluents of these industries make their way to agricultural lands where it contaminates the crop and ultimately reach the rest of the human population (Rani *et al*., 2014). Another widespread source of cadmium is tobacco smoke (Friberg, 1983). The fact that the clearance half-life of cadmium from human body is 25 years (Bernhoft, 2013; Aflanie *et al*., 2015) makes it all the more hazardous.

Once cadmium enters into blood, it binds to sulfhydryl group- containing protein e.g. metallothionein (Bernhoft, 2013). Within the human body it causes various disorders related to its toxicity, ranging from oxidative stress (Cuypers *et al*., 2010; Matovi´c *et al*., 2011; Patra *et al*., 2011), depletion of glutathione to osteoporosis, anaemia, eosinophilia and cancer (Valko *et al*., 2005). In fact, cadmium has been classified as a type I carcinogen by International Agency for Cancer Research (IARC, 1993, Arroyo *et al*., 2012).

**Microbial bioremediation of cadmium**

Different species of genus*Bacillus* like *B. subtilis* (Gayathramma *et al*., 2013), *B. cereus* (Arivalagan *et al*., 2014), *B. safensis* (Priyalaxmi *et al*., 2014), *B.licheniformis* (Shameer, 2016), and *B. thuriengiensis* (Kumar *et al*., 2016) have been isolated from contaminated soils and water all over the world. The rate of bioremediation of cadmium is dependent on many factors- one of them being initial cadmium concentration. Reports have indicated that *B. subtilis*has a maximum cadmium reduction potential at 200 µg/ml but not beyond this (Gayathramma *et al*., 2013). This can be explained by saturation effect of metal binding sites and due to increased toxicity of cadmium above this level leading to decreased cellular growth of the organism (Pan *et al*., 2009). This has been proved by the results of the same study which showed a marked reduction in the bioremediation potential of *B. subtilis*for cadmium at increased concentration of 250 µg/ml. These results were corroborated in a study by Priyalaxmi *et al*., (2014), performed on *B. safensis*, isolated from mangrove sediments. It showed 83.5% reduction at 40 ppm concentration of cadmium while the reduction increased to 98% upon increasing the concentration of cadmium to 60 ppm.

pH is another factor playing an important role in bioremediation of heavy metals. Changes in surrounding pH affects the surface charge of cell wall by influencing the negatively charged functional groups and their dissociation (Özdemir *et al*., 2013). This has been well established in a study conducted by Arivalagan *et al*., 2014. *B. cereus* was isolated from soil near electroplating industry and grown in presence of cadmium, *in vitro*. At pH 2, the organism showed insignificant absorption (Vimala and Das, 2009), due to low ionization of functional groups (Al-Garni, 2007; Bulgariu and Bulgariu, 2012; Özdemir *et al*., 2013). Also, the high concentration of $H^+$ at acidic pH competes for the available binding sites causing protonation of the cell wall (Yan and Viraraghavan, 2003). The study further reports that at moderately acidic pH 4, the negative charges on the cell wall increases and concentration of proton decreases (Rathinam *et al*., 2010) leading to more reduction of cadmium. Further at pH 6 maximum reduction of cadmium was reported as a result of complete deprotonation of functional groups like carboxyl and amino groups (Gupta and Rastogi, 2008; Xiao *et al*., 2010). Above this pH, a marked reduction in absorption was observed. This has been explained by increase in hydroxyl group which reacts with cadmium and precipitates it (Vimala and Das, 2009; Zhou *et al*., 2009; Xiao *et al*., 2010; Rathinam *et al*., 2010; Hossain and Aditya, 2013).

Biosorption is an energy dependent process and hence temperature plays an important role in the efficiency of metal removal by it (Congeevaram *et al*., 2007; Kao *et al*., 2009; Masoudzadeh *et al*., 2011). This efficiency increases or decreases with change in temperature that affects cell wall and its functional moieties by changing the stability and conformation of cell wall and the ionization state of functional groups (Li and Yuan, 2006; Congeevaram *et al*., 2007; Kao *et al*., 2009). Arivalagan and his team cultured *B. cereus* at 25, 35 and 45°C. Maximum cadmium removal was recorded at 35°C (72%) where a tremendous increase in biosorption efficacy was recorded as compared to 25°C (4%), the reason being increase in pore size as a result of which more surface is available for biosorption (Saleem *et al*., 2007; Rathinam *et al*., 2010). It also increases rate of diffusion and decreases viscosity of medium leading to increased efficacy of cadmium removal (Arivalagan *et al*., 2014). However, when the temperature increased from 35°C to 45°C, cadmium biosorption decreased. This may have happened due to destruction of the cadmium binding sites on cell wall by bond rupture leading to weaker cadmium binding potential (Meena *et al*., 2005; Dursun, 2006; Sari and Tuzen, 2008; Sulaymon *et al*.,2013).

**Mechanism of bioremediation of cadmium**

Due to their high surface area to volume ratio, bacteria have a remarkable capacity to adsorb metals from solution (Beveridge, 1989). They can perform this biosorption passively by mechanism such as surface precipitation, ion exchange or surface complexation (Le Cloirec and Andrès, 2005). Since this process is metabolism independent it can be performed by live as well as dead cells. This is in contrast to bioaccumulation where only live cells uptake the heavy metals actively rather than passively. Most of the studies on cadmium bioremediation have been conducted with live biomass but some others have proved that reduction in cadmium from cadmium-contaminated sites can be done with dead biomass too (Garcia *et al*., 2016). Since biosorption is a surface phenomenon, the cell wall of *Bacillus* sp. showed morphological and physiological changes after cadmium sorption. This was studied using SEM-EDX and FTIR (Nithya *et al*., 2011). A zeta potential analysis of *B. cereus* RC1 after cadmium adsorption determined that surface complexation and electrostatic interactions were important for biosorption (Huang *et al*., 2014). This biosorption capacity of *Bacillus* sp. is attributed to the various functional groups present on the cell wall. In addition to these functional groups, extracellular polymeric substance (EPS) also participates in biosorption. The constituents of EPS include carbohydrates and proteins and their derivatives in their homopolymeric or heteropolymeric form (Shameer, 2016). The advantages that bacterial cells gain from EPS production are many but essentially that of formation of biofilm which helps in metal and antibiotic resistance (Shameer, 2016). A study has proven that *B. licheniformis* NSPA5, *B. cereus* NSPA8 and *B.subtilis* NSPA13 produce EPS which gives these microorganisms resistance to cadmium and partakes in reduction of cadmium concentration (Shameer, 2016). These results have been corroborated by another study (Chauhan *et*

*al*., 2017). In the same study, TEM analysis of EPS of unidentified isolates showed entrapment of cadmium within it. This could be due to the presence of active carboxylic groups as determined by FTIR of the extracellular polymeric substrate of *Bacillus* sp. (Suh *et al*., 1993; Ganesh *et al*., 2004; Shameer, 2016).

Metal resistant genes in microorganisms can be either plasmid borne or chromosomally encoded. Different studies have performed plasmid curing of cells of cadmium resistant *Bacillus* sp. showing no change in their biosorption potential. Hence, it was concluded that cadmium resistance in *Bacillus* sp. is due to genes present on its chromosome (Mahler *et al*., 1986; Nithya *et al*., 2011; Chauhan *et al*., 2017). An interesting observation was made in a study conducted by Huang *et al*., (2014) on *B. cereus* RC1. They reported that if concentration of $Cd^{2+}$ was below 20mg/L then the predominant mechanism of bioremediation is bioaccumulation whilst above it, it is biosorption indicating that these mechanisms are dependent on initial concentration of cadmium.

**Nickel [Ni (II)]**

**Toxicity of nickel**

Nickel enters water, air and soil through natural sources like volcanic emissions, weathering of rocks and soil and solubilisation of nickel compounds from soil and through anthropogenic sources i.e. release of nickel containing effluents from industries like electroplating industry, battery industry, catalyst industry and electronic equipment industry (Duda-Chodak and Blaszczyk, 2008). This has hazardous effect on human health (Barceloux and Barceloux, 1999; Denkhaus and Salnikow, 2002). Nickel enters the human body via inhalation, ingestion and absorption through skin (Duda-Chodak and Blaszczyk, 2008). In blood, nickel is transported by binding mostly to albumin but also to histidine and á2- macroglobulin (Glennon and Sarkar, 1982; Kasprzak *et al*., 2003). The symptoms exhibited in nickel toxicity vary according to time

**Table 1.** Various bacterial genera performing bioremediation of different heavy metals

| S. No. | Genus | Species | Heavy metal | References |
|---|---|---|---|---|
| 1 | *Bacillus* | *licheniformis* | Pb, Cr, Cu | Syed and Chinthala, 2015 |
| | | | Cu, Cd, Zn | Issazadeh *et al*., 2011 |
| | | *cereus* | Pb, Cr, Cu | Syed and Chinthala, 2015 |
| | | | Cu, Cd, Zn | Issazadeh *et al*., 2011 |
| | | *subtilis* | Pb, Cr, Cu | Syed and Chinthala, 2015 |
| | | | Pb, Cu, Cd, Zn | Issazadeh *et al*., 2011 |
| | | | Hg, Cd | Imam *et al*., 2016 |
| | | *carotarum* | Pb, Zn, Cr | Gupta *et al*., 2014 |
| | | *lentus* | Pb, Zn, Cr | Gupta *et al*., 2014 |
| | | *thuriengiensis* | Zn, Pb | Singh *et al*., 2015 |
| | | *amyloliquefacians* | Cd, Zn, Cu, Pb | Issazadeh *et al*., 2011 |
| | | *sphaericus* | Cu, Ni, Cr | Al-Daghistani, 2012 |
| | | *pumilus* | Cu, Ni, Cr | Al-Daghistani, 2012 |
| | | *megaterium* | Cu, Fe, Zn, Mn | Stefanescu, 2015 |
| 2 | *Escherichia* | *coli* | Zn, Cu, Cd, Hg | Vijayadeep and Sastry, 2014 |
| | | | Zn, Cd, Cr, Ni | Oaikhena *et al*., 2016 |
| 3 | *Pseudomonas* | *aeroginosa* | Cu, Cr, Fe, Zn | Awasthi *et al*., 2015 |
| | | | Cu, Cr, Zn, Pb, Co, Cd, Hg, Ni | Haroun *et al*., 2017 |
| | | *fluorescens* | Pb, Zn | Meliani and Bensoltane, 2016 |
| | | *putida* | Zn, Cd, Co, Ni, Cu, Cd | Bhojiya and Joshi, 2016 |
| | | | Fe, Mn | Khedr *et al*., 2015 |
| 4 | *Proteus* | *vulgaris* | Cd, Cr, Ni, Zn | Oaikhena *et al*., 2016 |
| 5 | *Klebsiella* | *pneumoniae* | Cd, Cr, Ni, Zn | Oaikhena *et al*., 2016 |
| 6 | *Enterobacter* | *cloacae* | Pb, Cd, Ni | Banerjee *et al*., 2015 |
| | | *arburiae* | Cd, Ni | Bhagat *et al*., 2016 |

and dose of exposure causing different health problems ranging from nausea, giddiness and vomiting (Duda-Chodak and Blaszczyk, 2008) to respiratory disorders and cardiovascular disorders and even death (Oller *et al*., 1997; McGregor *et al*. 2000; Seilkop and Oller 2003).

**Microbial bioremediation of nickel**

Nickel-resistant *Bacillus* sp. have been isolated from waste water treatment plant (Rajbanshi, 2008) and contaminated soils (Shoeb *et al*., 2010; Aryal, 2015; Taran *et al*., 2015). They have shown maximum nickel removal capacity from 50µg/ml to 150 µg/ml of initial nickel concentration (Abdel-Monem *et al*., 2010; Lei *et al*., 2014; Zhang *et al*., 2016; Uthra and Kadirvelu, 2017). Studies have shown that factors such as pH, temperature, contact time and initial nickel concentration affect the efficiency of nickel bioremediation by both dead and live cells of *Bacillus* sp. In these studies it was observed that maximum removal of nickel by live cells occured at neutral pH (Abdel-Monem *et al*., 2010; Salman, 2014; Taran *et al*., 2015; Naskar *et al*., 2016; Jain *et al*., 2017) while one has reported nickel removal at slightly acidic pH i.e. pH 5 (Aryal, 2015). Temperature too played a crucial role in bioremediation of nickel where optimum temperature was observed in the mesophilic range i.e. 25°C to 40°C (Salman, 2014; Aryal, 2015; Taran *et al*., 2015; Naskar *et al*., 2016) for live cells. Optimum contact time varied from 25 mins (Aryal, 2015) to 24 hrs (Taran *et al*., 2015). However, in case of nickel removal using dead cells of *Bacillus* sp. as adsorbent, optimum pH varied from pH 4 (Zhang *et al*., 2016) to pH 8 (Gheethi *et al*., 2017) while optimum temperature was from 30°C to 37°C (Gheethi *et al*., 2017; Uthra and Kadirvelu, 2017).

**Mechanism of bioremediation of nickel**

The studies performed by various scientists proved time to time that both dead and live cells of *Bacillus* sp. exhibit the capacity for nickel removal, thus highlighting the possibility that biosorption is the primary mechanism for nickel bioremediation. In 2015, Aryal *et al*. demonstrated with the help of FTIR, that –COOH and $–NH_2$ groups of *B. sphaericus* are responsible for nickel binding. They further proved this by studying the effect of temperature on nickel removal. They observed that with increase in temperature from 20°C to 40°C the bioremediation potential of the organism too was elevated. However, on increasing the temperature further, this potential dropped due to decrease in surface activity. They concluded this study by reporting that nickel bioremediation by *B. sphaericus* is through biosorption and is also an exothermic process. Another published report has shown similar findings (Sari *et al*., 2008). After nickel exposure, change was observed in surface morphology of dead *B. laterosporus* MTCC 1628, with the help of SEM-EDX, further corroborating findings that nickel bioremediation is by biosorption. Similar changes were observed

**Table 2.** Various probiotic bacterial genera performing bioremediation of different heavy metals

| S. No. | Genus | Species | Heavy metal | References |
|---|---|---|---|---|
| 1 | *Lactobacillus* | *plantarum* | Cd, Pb | Kirillova *et al*., 2017 |
| | | | Cr | Wu *et al*., 2017 |
| | | *fermentum* | Cd, Pb | Kirillova *et al*., 2017 |
| | | *casei* | Cd, Pb, Ni | Ogunnusi and Oyetunji, 2017 |
| | | *paracasei* | Cd, Hg, Pb, Be, As | Fang *et al*., 2018 |
| | | *acidophilus* | Cd, Hg, Pb, Be, As | Fang *et al*., 2018 |
| | | *reuteri* | Cd, Hg, Pb, Be, As | Fang *et al*., 2018 |
| | | *rhamnosus* | Cd, Hg, Pb, Be, As | Fang *et al*., 2018 |
| | | *kefir* | Cd | Gerbino *et al*., 2014 |
| 2 | *Bifidobacterium* | *longum* | Cd, Hg, Pb, Be, As | Fang *et al*., 2018 |
| | | *lactis* | Cd | Halttunen *et al*., 2007 |
| 3 | *Bacillus* | *coagulans* | Cr, Pb, | Belapurkar *et al*., 2016 |
| | | | Ni | Belapurkar *et al*., 2018 |
| | | | Cd | Majlesi *et al*., 2016 |
| | | clausii | Pb, Zn | Aleksey *et al*., 2014 |

in *B. licheniformis* (Jain *et al*., 2017). These results are suggestive of a passive process i.e. biosorption which is a surface phenomenon.

The species of genus *Bacillus* are Gram positive, rod shaped spore formers. Their cell wall offers many negatively charged functional groups like hydroxyl, carboxylate, sulphate and amino groups (Vijayaraghavan and Yun, 2008). These groups exhibit ionic interaction with positively charged $Ni^{2+}$ ions after initial metal complex formation and neutralization of chemically active sites (Beveridge, 1989). When cells of *B. subtilis* 117S were pretreated with sodium azide, mercuric chloride and formaldehyde, a decrease in nickel removal capacity of cells was observed. It occurred due to esterification of carboxyl groups and methylation of amino groups. This hereby concluded the importance of functional groups present on cell wall of *Bacillus* sp. in nickel bioremediation (Abdel-Monem *et al*., 2010).

In 2009, Shoeb *et al*. isolated *B. cereus* CMG2K4 from metal contaminated soil and by plasmid curing they were able to demonstrate that nickel bioremediation capacity of this organism is chromosomally borne. The organism also produced a 36KDa protein upon exposure to 1 mM $NiCl_2$. This was identified as flagellin, a flagellar protein. It was hypothesised that it was overproduced under heavy metal stress to increase motility of *B. cereus* CMG2K4 to avoid areas with high nickel concentration and move to a potentially new site devoid of toxic substances (Ottemann and Miller, 1997). This suggests that not only one, but several mechanisms are responsible for bioremediation of heavy metals.

**Microbial bioremediation of cadmium and nickel by lactic acid bacteria (LABs) and other probiotic species of genus *Bacillus***

In 2001, WHO defined probiotics as, "live microorganisms that when administered in adequate amount confer a health benefit to the host" (FAO/WHO, 2001). These health benefits in general include treatment of digestive disorders and strengthening of immune system (Huët and Puchooa, 2017). The probiotic microorganisms can be either inhabitants of gastrointestinal tract (GIT) like LABs or can be isolated from different sources in the environment like probiotic species of genus *Bacillus.*

LABs are a vast group of organisms, their main characteristic being production of lactic acid as major end-product of carbohydrate fermentation. They are generally Gram positive cocci and rods. *Lactobacillus*, *Pediococcus*, *Streptococcus*, *Leuconostoc* and *Bifidobacterium* are some of its important representative genera (Todar, 2004). They have unique properties of being able to reduce the concentration of toxic substance from GIT (Meriluoto *et al*., 2005) as well as bioremediation of heavy metals *in vitro* and *in vivo* (Halttunen *et al*., 2007; Zhai *et al*., 2017). They owe this ability to bind heavy metals due to specific constituents found in their cell wall like teichoic acid and lipoteichoic acid along with some polysaccharides and EPS (Delcour *et al*., 1999).

An extensive study was performed by Halttunen *et al*., (2007) on bioremediation of cadmium by 3 species of *Bifidobacterium* i.e. *B. longum* 2C, *B. longum* 46, and *B. lactis* Bb12, 3 species of *Lactobacillus* i.e. *L. rhamnosus* GG, *L. casei*Shirota and *L. fermentum*ME3 and 2 commercial starter cultures. For a contact time of 1 hr, *B. longum* 46 showed highest cadmium removal of 54.7 mg metal/ g dry biomass followed by *L. fermentum*ME3 and *B. lactis* Bb12. The test pH ranged from acidic to alkaline and interestingly, a pH drop was observed at all pH values except for highly acidic ones. This pH drop indicates that biosorption occurs by means of ion exchange, where $H^+$ on cell wall is being replaced by $Cd^{2+}$ and causes pH to decrease upon its release into the surrounding medium. With increase in pH, the binding capacity for cadmium increased till pH 6 where it was maximum (60-73%). This variation in biosorption potential results from competition between protons and heavy metal cations for the negatively charged binding sites (Huang *et al*., 1991).

When the bacterial concentration (biomass) was increased the binding efficacy also improved due to availability of binding sites in excess. This binding is quite strong in *L. plantarum* as it did not show any metal desorption upon multiple washings with Milli- Q water (Kumar *et al*., 2017). Another observation made was that temperature variations did not affect the bioremediation potential of these microorganisms; emphasizing that this process is temperature independent. Similar effect was observed when bacteria were killed by boiling them. This elucidates

that the probable mechanism of bioremediation is passive i.e. biosorption rather than active i.e. bioaccumulation. These results, however contradict the reports of Hao *et al*., (1999a) where it was observed that when *L. plantarum* cells were poisoned or kept at low temperature no cadmium removal happened, suggesting that the nature of this mechanism is energy dependent.

Various metal ions interfere and inhibit uptake of other heavy metals. In *L. plantarum* $Cd^{2+}$ removal was inhibited by $Mn^{2+}$ but not by $Zn^{2+}$, $Cu^{2+}$, $Co^{2+}$ etc. The high concentration of $Mn^{2+}$ in *L. plantarum* helps to reduce toxicity of superoxide radical ions by scavenging them (Archibald and Fridovich, 1981a and b, Archibald and Fridovich, 1982a and b). The transport system of $Mn^{2+}$ is linked to uptake of $Cd^{2+}$ (Hao *et al*., 1999a). In this context, *L. plantarum*has showed the presence of two different cadmium uptake systems: one which is independent of $Mn^{2+}$ starvation but has low affinity, while the other is with high affinity and induced by $Mn^{2+}$ starvation but inhibited in presence of $Mn^{2+}$ (Hao *et al*., 1999a). Upon characterization of genes involved in cadmium and manganese uptake, gene mntA was identified as the one encoding high affinity transporter system for $Cd^{2+}$ and $Mn^{2+}$ uptake. This gene belonged to a family of P-type ATPases (Hao *et al*., 1999b).

*Lactobacillus* strains *L. kefir* CIDCA 8348 and *L. kefir* JCM 5818 were evaluated for their ability to bind cadmium *in vitro* and protect eukaryotic HepG2 cell lines from cadmium toxicity. When HepG2 cell lines were exposed to cadmium pre-incubated with these strains, the viability of the cell line increased as compared to direct exposure of cadmium, where the efficiency of *L. kefir* JCM 5818 was higher. This was attributed to its non-aggregative nature as compared to *L. kefir*CIDCA 8348, thus providing more surface area and hence more binding sites for cadmium (Gerbino *et al*., 2014). Thus, the study proved ability of *Lactobacillus* sp. to bioremediate cadmium as well as reduce cadmium toxicity in eukaryotic cells.

Heavy metal stress also leads to synthesis of proteins which may mitigate the toxicity caused by heavy metals. One such glycoprotein isolated from *L. plantarum* L67 inhibits inflammatory factors such as AP-1, mitogen activated protein kinases and nitric oxide synthase expressed by RAW 264.7 cells under $Cd^{2+}$ stress (Song *et al*., 2016).

Biological evidence has been provided by Zhai *et al*., (2013) where they have reported that *L. plantarum*CCFM8610 has reduced cadmium toxicity *in vivo*. This study was performed on male Kunming mice, where they were exposed to cadmium stress. In presence of dead and live *L. plantarum,* faecal matter showed increasing cadmium concentration as compared to control groups. Due to oxidative stress in body caused by acute cadmium exposure, liver too showed histopathological damage such as necrosis of hepatocytes (Tzirogiannis *et al*., 2003). This resulted in an increase in malondialdehyde (MDA-indicator of lipid peroxidation), decreased glutathione (GSH) (consumed to reduce reactive oxygen species (ROS) produced as a side effect of cadmium toxicity) (Bagchi *et al*., 1996), and decrease in activity of superoxide dismutase (SOD) and catalase (CAT) (both enzymes with antioxidant property) in liver and kidney (Thijssen *et al*., 2007). When mice were treated with *L. plantarum*all these symptoms were alleviated, more so with live cells as compared to dead cells. This specific antioxidant property of *Lactobacillus* has also been reported in other studies (Güven *et al*., 2003; Zhang *et al*., 2010).

Another mechanism is that this species reduces cadmium toxicity by reducing its absorption from the intestine. If cadmium is absorbed, it induces synthesis of metallothionein (MT) (Nordberg and Nordberg, 2000) and the Cd- MT complex is stored in liver. However, if cadmium concentration exceeds metallothionein production, then it damages liver and kidney (Nordberg and Nordberg, 1987; Klaassen and Liu, 1997). *L. plantarum*CCFM8610 rapidly binds cadmium before it can be absorbed in intestine and excretes it in faeces (Zhai *et al*., 2013).

Under *in vitro* conditions both live and dead *L. plantarum*CCFM8610 had similar cadmium binding ability but live *L. plantarum* proved more efficient in reducing cadmium concentration because it stimulated intestinal peristalsis and reduced oxidative stress caused by cadmium exposure (Zhai *et al*., 2013).

There are many species belonging to genus *Bacillus* including *B. clausii* and *B.*

*coagulans* which have both the remarkable properties together i.e. they have probiotic potential as well as capacity for bioremediation of heavy metals (Belapurkar *et al*., 2016). When male Wistar rats were fed with a synbiotic diet i.e. probiotic microorganisms (*B. coagulans*and *L. plantarum*CNR 273) together with a prebiotic (inulin), their liver enzymes are improved post cadmium exposure. Some biochemical parameters such as aspartate aminotransferase (AST), alanine aminotransferase (ALT), bilirubin and blood urea nitrogen (BUN) that were enhanced by cadmium, decreased significantly and cadmium accumulation in liver and kidney was reduced when administered with this synbiotic diet (Jafarpour *et al*., 2017). Similar results were reported by a previous study (Majlesi *et al*., 2016).

Immobilized *B. coagulans* also exhibited a high adsorption capacity of 68.4 mg/ g of biomass in nickel bioremediation (Lei *et al*., 2014)

## CONCLUSION

In today's scenario of heavy metal pollution causing hazardous effects on human life, the role of microorganisms suggest an easy and cheap alternative for their remediation. The mechanism of bioaccumulation and biosorption have shown potential for bioremediation in environmental and probiotic species of genus *Bacillus* as well as in other probiotic genera. They have shown convincing ability of potential gut remediation of heavy metals cadmium and nickel, suggesting their pivotal role in solving the problem of heavy metal toxicity commonly seen as a side effect of industrialization.

## ACKNOWLEDGEMENT

The authors are grateful to Ar. AchalChaudhary, President, IPS Academy and Dr. Sanjay Nagar, Professor and Head, Department of Biotechnology, IPS Academy, for their encouragement and timely help in this review.

## REFERENCES

1. Abdel-Monem, M.O., Al-Zubeiry, A.H.S., Al-Gheethi, A.A.S.Biosorption of nickel by *Pseudomonas cepacia* 120S and *Bacillus subtilis* 117S. *Water Sci. Technol.* 2010; **61**: 2994-3007.
2. Aflanie, I., Muhyi, R., Suhartono, E. Effect of heavy metal on malondialdehyde and advanced oxidation protein products concentration: A focus on arsenic, cadmium, and mercury. *J. Med. Bioeng.* 2015; **4**:332-337.
3. Ahmed, S., Islam, M.R., Ferdousi, J., Iqbal, T.S. Probiotic *Lactobacillus* sp. with bioremediation potential of toxic heavy metals. *Bangladesh J. Microbiol.* 2017; **34**:43-46.
4. Aiking, H., Stijnman, A.C., Garderen, V., Heerikhuizen, H.V., Riet, J.V.T. Inorganic phosphate accumulation and cadmium detoxification in *Klebsiellaaerogenes*NCTC 418 growing in continuous culture. *Appl. Environ. Microbiol.* 1984;**47**:374–377.
5. Al-Daghistani, H. Bio-remediation of Cu, Ni and Cr from rotogravure wastewater using immobilized, dead, and live biomass of indigenous thermophilic*Bacillus* species.*Internet J. Microbiol*. 2012;**10**:1-10.
6. Aleksey, S., Olga, K., Aleksandr, V., Alena, B., Elena, D. The use of probiotic preparations on basis of bacteria of a genus *Bacillus* during intoxication of lead and zinc. *Life Sci. J.*2014; **11**:18-20.
7. Al-Garni, S.M.Biosorption of lead by Gram-ve capsulated and non-capsulated bacteria. *Water SA*. 2007; **31:**345–350.
8. Archibald, F. S., Fridovich, I. Manganese and defenses against oxygen toxicity in *Lactobacillus plantarum*. *J. Bacteriol.* 1981a;**145**:442–451.
9. Archibald, F. S., Fridovich, I. Manganese, superoxide dismutase, and oxygen tolerance in some lactic acid bacteria. *J. Bacteriol.* 1981b;**146**:928–936.
10. Archibald, F. S., Fridovich, I. Investigation of the state of the manganese in *Lactobacillus plantarum*. *Arch. Biochem. Biophys*. 1982a;**215**:589–596.
11. Archibald, F. S., Fridovich, I. The scavenging of the superoxide radical by manganous complexes: *in vitro*. *Arch. Biochem. Biophys.* 1982b;214:452–463.
12. Arivalagan, P., Singaraj, D., Haridass, V., Kaliannan, T. Removal of cadmium from aqueous solution by batch studies using *Bacillus cereus*. *Ecol. Eng.* 2014; **71**:728-735.
13. Arroyo, V.S., Flores, K.M., Ortiz, L.B., Gómez-Quiroz, L.E., Gutiérrez-Ruiz, M.C. Liver and cadmium toxicity. *J. Drug. Metab. Toxicol.*2012; **S5**:1-7
14. Aryal, M. Removal and Recovery of nickel ions from aqueous solutions using *Bacillus sphaericus*biomass. *Int. J. Environ. Res.* 2015; **9**:1147-1156.
15. Awasthi, G., Chester, A., Chaturvedi, R., Prakash,

J. Study on Role of *Pseudomonasaeruginosa* on Heavy Metal Bioremediation. *Int. J. Pure App. Biosci.* 2015; **3**:92-100.

16. Bagchi, D., Bagchi, M., Hassoun, E., Stohs, S. Cadmium-induced excretion of urinary lipid metabolites, DNA damage, glutathione depletion, and hepatic lipid peroxidation in Sprague-Dawley rats. *Biol. Trace Elem. Res.* 1996; **52:**143–154.
17. Banerjee, G., Pandey, S., Ray, A. K., Kumar, R. Bioremediation of heavy metals by a novel bacterial strain *Enterobactercloacae* and its antioxidant enzyme activity, flocculant production, and protein expression in presence of lead, cadmium, and nickel. *Water Air Soil Pollut.* 2015; **226**:1-9.
18. Barceloux, D.G., Barceloux, D.Nickel. *J. Toxicol. Clin. Toxicol.* 1999; **37**:239-258.
19. Belapurkar, P., Goyal, P., Kar, A. *In vitro* evaluation of bioremediation capacity of a commercial probiotic, *Bacillus coagulans*, for chromium (VI) and lead (II) toxicity. *J. Pharm. Bioallied Sci.* 2016; **8**: 272-276.
20. Belapurkar, P., Goyal, P., Kar, A.Potential assessment of *Bacillus coagulans*for bioremediation of Zn (II) and Ni (II): an *in vitro* study. *Eur. J. Biomed. Pharm. Sci.*2018; **5**:627-632
21. Bernhoft, R.A. Cadmium toxicity and treatment. *Sci. World J.* 2013: 1-7.
22. Beveridge, T.J. Role of cellular design in bacterial metal accumulation and mineralization. *Annu. Rev. Microbiol.* 1989; **43**:147–171.
23. Bhagat, N., Vermani, M., Bajwa, H.S. Characterization of heavy metal (cadmium and nickle) tolerant Gram negative enteric bacteria from polluted Yamuna River, Delhi. *Afr. J. Microbiol. Res.* 2016; **10**:127-137.
24. Bhojiya, A.A., Joshi, H. Heavy metal tolerance pattern of *Pseudomonasputida* isolated from heavy metal contaminated soil of Zawar, Udaipur (India). *Int. J. Innov. Knowl. Concepts* 2016; **4**:58-64
25. Borma, L.D.S., Ehrlich, M., Barbosa, M.C. Acidification and release of heavy metals in dredged sediments. *Can. Geotech. J.*2003; **40**:1154–1163.
26. Borrok, D., Fein, J.B., Kulpa, C.F. Proton and Cd adsorption onto natural bacterial consortia: Testing universal adsorption behavior. *Geochim. Cosmochim. Ac.*2004; **68**:3231–3238.
27. Bradl, H.B.: Sources and origins of heavy metals. In: *Heavy Metals in the Environment: Origin, Interaction and Remediation* (Bradl HB, ed) London: Academic Press. 2005; pp 1-27.
28. Bulgariu, D., Bulgariu, L. Equilibrium and kinetics studies of heavy metal ions biosorption on green algae waste biomass. *Bioresour. Technol.* 2012; **103**: 489–493.
29. Chaney, R.L., Li, Y.M., Brown, S.L., Homer, F.A., Malik, M., Angle, J.S., Baker, A.J.M, Roger, D., Reeves, R.D., Mel Chin, M.: Improving metal hyperaccumulator wild plants to develop commercial phytoextraction systems: Approaches and progress. In: *Proceedings of the Symposium on Phytoremediation, 4th International Conference on the Biogeochemistry of Trace Elements* (Banuelos GS, Terry N, eds)2000; pp 129-158
30. Chaney, R.L., Malik, M., Li, Y.M., Brown, S.L., Brewer, E.P.,Angle, J.S., Baker, A.J. Phytoremediation of soil metals. *Curr. Opin. Biotechnol.*1997; **8**:279-284.
31. Chang, L.W., Meier, J.R., Smith, M.K. Application of plant and earthworm bioassays to evaluate remediation of a lead-contaminated soil. *Arch. Environ. Contam. Toxicol.* 1997; **32**:166-171.
32. Chauhan, M., Solanki, M., Nehra, K. Putative mechanism of cadmium bioremediation employed by resistant bacteria. *Jordan J. Biol. Sci.* 2017; **10**:101-107.
33. Congeevaram, S., Dhanarani, S., Park, J.,Dexilin, M., Thamaraiselvi, K.Biosorption of chromium and nickel by heavy metal resistant fungal and bacterial isolates. *J. Hazard. Mater.* 2007; **146**:270–277.
34. Cuypers, M., Plusquin, T., Remans, T., Jozefczak, M., Keunen, E., Gielen, H., Opdenakker, K., Nair, A.R., Munters, E., Artois, T.J., Nawrot, T., Vangronsveld, J., Smeets, K.Cadmium stress: an oxidative challenge. *BioMetals*2010; **23**:927–940.
35. Delcour, J., Ferain, T., Deghorain, M., Palumbo, E., Hols, P. The biosynthesis and functionality of the cell-wall of lactic acid bacteria. *Antonie Van Leeuwenhoek* 1999; **76**:159-184.
36. Denkhaus, E., Salnikow, K.Nickel essentiality, toxicity, and carcinogenicity. *Crit. Rev. Oncol. Hematol.*2002; **42**:35-56.
37. Duda-Chodak, A., Blaszczyk, U.,. The impact of nickel on human health. *J. Elementol.* 2008; **13**:685-693.
38. Dursun, A.Y. A comparative study on determination of the equilibrium, kinetic and thermodynamic parameters of biosorption of copper(II) and lead(II) ions onto pretreated*Aspergillusniger*. *Biochem. Eng. J.* 2006; **28**:187–195.
39. Fang, S.T., Cheng, D.E., Huang, Y.T., Hsu, T.Y., Lu, H.H.S.A pilot study of the influence of probiotics on hair toxic element levels after long-term supplement with different Lactic Acid

bacteria strains. *J. Prob. Health* 2018; **6**:1-8

40. FAO/WHO. Evaluation of Health and Nutritional Properties of Probiotics in Food Including Powder Milk with Live Lactic Acid Bacteria. In: *Food and Agriculture Organization of the United Nations and World Health Organization Expert Consultation Report* 2001; pp 1-50.
41. Fergusson, J.E. (ed): The heavy elements: chemistry, environmental impact and health effects. Oxford: Pergamon Press 1990.
42. Friberg, L. Cadmium. *Annu. Rev. Public Health* 1983; **4**:367–373.
43. Ganesh, K.C., Han-Seung, J., Jang-Won, C., Yoon-Moo, K., Chung-Soon, C.,. Purification and characterization of an extracellular polysaccharide from haloalkaliphilic*Bacillus* sp. I-450. *Enzyme Microb. Technol.* 2004; **34**:673–681
44. García, R., Campos, J., Cruz, J.A., Calderón, M.E., Raynal, M.E., Buitrón, G.Biosorption of Cd, Cr, Mn, and Pb from aqueous solutions by *Bacillus* sp. strains isolated from industrial waste activate sludge. *TIP RevistaEspecializada en CienciasQuímico-Biológicas* 2016; **19**:5-14.
45. Gayathramma,.K., Pavani, K.V., Singh, A.R., Deepti, S. Role of *Bacillus subtilis* in bioremediation of heavy metals. *Int. J. Biomed. Res.*2013; **6**:6-11.
46. Gerbino, E., Carasi, P., Tymczyszyn, E.E., Gómez-Zavaglia, A. Removal of cadmium by *Lactobacillus kefir* as a protective tool against toxicity. *J. Dairy Res.* 2014; **81**:280-287.
47. Gheethi, A.A., Efaq, A.N., Mohamed, R.M., Abdel-Monem, M.O., Abdullah, A.H., Hashim, M.A.,. Bio-removal of nickel ions by *Sporosarcinapasteurii* and *Bacillus megaterium*, a comparative study. *IOP Conf. Ser.: Mater. Sci. Eng.*2017; **226**:1-7
48. Glennon, J.D., Sarkar, B.Nickel (II) transport in human blood serum: studies of nickel (II)-binding human albumin and to native-sequence peptide, and ternary complex formation with L-histidine. *Biochem. J.* 1982; *203*:15-23.
49. Gupta, M.K., Kiran, K., Amita, S., Shikha, G. Bioremediation of heavy metal polluted environment using resistant bacteria. *J. Environ. Res. Dev.*2014; **8**:883-889.
50. Gupta, V.K., Rastogi, A. Equilibrium and kinetic modelling of cadmium (II) biosorption by non-living algal biomass *Oedogonium* sp. from aqueous phase. *J. Hazard. Mater.* 2008; **153**:759–766.
51. Güven, A., Güven, A., Gülmez, M. The effect of kefir on the activities of GSH-Px, GST, CAT, GSH and LPO levels in carbon tetrachloride-induced mice tissues. J. Vet. Med. B Infect. *Dis. Vet. Public Health* 2003; **50**:412– 416.
52. Halttunen, T., Salminen, S., Tahvonen, R. Rapid removal of lead and cadmium from water by specific lactic acid bacteria. *Int. J. Food Microbiol.* 2007; **114**:30-35.
53. Hans Wedepohl, K. The composition of the continental crust. *Geochim. Cosmochim. Acta* 1995; **59**:1217–1232.
54. Hao, Z., Chen, S., Wilson, D.B. Cloning, expression, and characterization of cadmium and manganese uptake genes from *Lactobacillus plantarum*. *Appl. Environ. Microbiol.* 1999b; **65**:4746-4752.
55. Hao, Z., Reiske, H. R., Wilson, D.B. Characterization of cadmium uptake in *Lactobacillus plantarum* and isolation of cadmium and manganese uptake mutants. *Appl. Environ. Microbiol.* 1999a;**65**:4741-4745.
56. Haroun, A., Kamaluddeen, K., Alhaji, I., Magaji, Y. and Oaikhena, E. Evaluation of heavy metal tolerance level (MIC) and bioremediation potentials of *Pseudomonasaeruginosa* isolated from Makera-Kakuri industrial drain in Kaduna, Nigeria. *Eur. J. Exp. Biol.* 2017; **7**:1-4
57. He, Z.L., Yang, X.E., Stoffella, P.J. Trace elements in agroecosystems and impacts on the environment. *J. Trace. Elem. Med. Biol.* 2005; **19**:125–140.
58. Hossain, A., Aditya, G. Cadmium biosorption potential of shell dust of the fresh water invasive snail *Physaacuta*. *J. Environ. Chem. Eng.* 2013; **1**:574–580.
59. Huang, C., Huang, C.P., Morehart, A.L. Proton competition in Cu (II) adsorption by fungal mycelia. *Water Res.* 1991; **25**:1365–1375.
60. Huang, F., Guo, C.L., Lu, G.N., Yi, X.Y., Zhu, L.D., Dang, Z. Bioaccumulation characterization of cadmium by growing *Bacillus cereus* RC-1 and its mechanism. *Chemosphere* 2014; **109**:134-142.
61. Huët, M.A.L., Puchooa, D. Bioremediation of heavy metals from aquatic environment through microbial processes: A potential role for probiotics? *J. Appl. Biol. Biotechnol.* 2017; **5**:14-23.
62. Imam, S.A., Rajpoot, I.K., Gajjar, B., Sachdeva, A., 2016. Comparative study of heavy metal bioremediation in soil by *Bacillussubtilis* and *Saccharomycescerevisiae*. Indian J. Sci. Technol.9, 1-7.
63. International Agency for Research on Cancer.: Beryllium, cadmium, mercury, and exposures in the glass manufacturing industry. In: *International agency for research on cancer monographs on the evaluation of carcinogenic risks to humans.* Lyon: IARC Scientific Publications. 1993; 58;

pp 119–237.

64. Issazadeh, K., Pahlaviani, M.R.M.K., Massiha, A. Bioremediation of toxic heavy metals pollutants by *Bacillus spp*. isolated from Guilan bay sediments, north of Iran. *Int. Conference Biotechnol. Environ. Manage. (IPCBEE)* 2011; **18**:67-71.
65. Jafarpour, D., Shekarforoush, S.S., Ghaisari, H.R., Nazifi, S., Sajedianfard, J., Eskandari, M.H. Protective effects of synbiotic diets of *Bacillus coagulans*, *Lactobacillus plantarum* and inulin against acute cadmium toxicity in rats. *BMC Complement. Altern. Med.* 2017; **17**:1-8.
66. Jain, A.N., Udayashankara, T.H., Lokesh, K.S., Sudarshan, B.L. Bioremediation of lead, nickel and copper by metal resistant *Bacillus licheniformis*isolated from mining site: optimization of operating parameters under laboratory conditions. *Int. J. Res. Eng. Technol.* 2017; **5**:13-32.
67. Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.*2014; **7**:60-72.
68. Kao, W.C., Wu, J.Y., Chang, C.C., Chang, J.S. Cadmium biosorption by polyvinyl alcohol immobilized recombinant *Escherichia coli*. *J. Hazard. Mater.* 2009; **169**:651–658.
69. Kasprzak, K.S., Sunderman Jr., F.W., Salnikow, K.Nickel carcinogenesis. *Mutat. Res*.2003; **533**:67-97.
70. Khedr, G., El-Dougdoug, A., Shaban, A., El Nil, I.A. Bioremediation of heavy metals by *Pseudomonasputida* isolated from groundwater in Egypt. *Int. J. Sci. Technol. Res.* 2015; **4**:71-75.
71. Kirillova, A.V., Danilushkina, A.A., Irisov, D.S., Bruslik, N.L., Fakhrullin, R.F., Zakharov, Y.A., Bukhmin, V.S., Yarullina, D.R. Assessment of resistance and bioremediation ability of *Lactobacillus* strains to lead and cadmium. *Int. J. Microbiol.***2017**, 1-7.
72. Klaassen, C.D., Liu, J. Role of metallothionein in cadmium-induced hepatotoxicity and nephrotoxicity. *Drug Metab. Rev.* 1997; **29**:79 –102.
73. Kumar, M., Kumar, V., Varma, A., Prasad, R., Sharma, A.K., Pal, A., Arshi, A., Singh, J. An efficient approach towards the bioremediation of copper, cobalt and nickel contaminated field samples. *J. Soils Sediments* 2016; **16**:2118-2127.
74. Kumar, N., Kumar, V., Panwar, R., Ram, C. Efficacy of indigenous probiotic *Lactobacillus* strains to reduce cadmium bioaccessibility - an *in vitro* digestion model. *Environ. Sci. Pollut. Res.* 2017; **24**:1241-1250.
75. Le Cloirec, P., Andrès, Y.: Bioremediation of heavy metals using microorganisms. In:*Bioremediation of aquatic and terrestrial ecosystems* (Fingerman M, Nagabhushanam R eds). Enfield: Science Publishers Inc. 2005; pp 97–140.
76. Lei, D.Y., Liu, Z., Peng, Y.H., Liao, S.B., Xu, H.Biosorption of copper, lead and nickel on immobilized *Bacillus coagulans* using experimental design methodologies. *Ann. Microbiol.* 2014; **64**:1371-1384.
77. Li, Z., Yuan, H. Characterization of cadmium removal by *Rhodotorula* sp. Y11. *Appl. Microbiol. Biotechnol.* 2006; **73**:458–463.
78. Mahler, I., Levinson, H.S., Wang, Y.I.N.G., Halvorson, H.O. Cadmium-and mercury-resistant *Bacillus* strains from a salt marsh and from Boston Harbor. *Appl. Environ. Microbiol.* 1986; **52**:1293-1298.
79. Majlesi, M., Shekarforoush, S., Ghaisari, H., Nazifi, S., Sajedianfard, J. Effect of *Bacilluscoagulans* and *Lactobacillusplantarum* as probiotic on decreased absorption of cadmium in rat. *J. Food Hyg.* 2016; **6**:25- 32.
80. Masoudzadeh, N., Zakeri, F., Lotfabad, T.B., Sharafi, H., Masoomi, F., Zahiri, H.S., Ahmadian, G., Noghabi, K.A.Biosorption of cadmium by *Brevundimonas* sp. ZF12 strain, a novel biosorbent isolated from hot-spring waters in high background radiation areas. *J. Hazard. Mater.* 2011; **197**:190–198.
81. Matovi´c, V., Buha, A.,Bulat, Z., Duki´c-Cosi´c, D. Cadmium toxicity revisited: focus on oxidative stress induction and interactions with zinc and magnesium. *Arh. Hig. RadaToksikol*. 2011; **62**:65–76.
82. McGregor, D.B., Baan, R.A., Partensky, C., Rice, J.M., Wilbourn, J.D.Evaluation of the carcinogenic risks to humans associated with surgical implants and other foreign bodies – a report of an IARC Monographs Programme Meeting. *Eur. J. Cancer.* 2000; **36**:307-313.
83. Meena, A.K., Mishra, G.K., Rai, P.K., Rajagopal, C., Nagar, P.N. Removal of heavy metal ions from aqueous solutions using carbon aerogel as an adsorbent. *J. Hazard. Mater.* 2005; **122**:161–170.
84. Meliani, A., Bensoltane, A. Biofilm-mediated heavy metals bioremediation in PGPR *Pseudomonas*. *J. Bioremediat. Biodegrad.* 2016; **7**:1-9
85. Meriluoto, J., Gueimonde, M., Haskard, C.A., Spoof, L., Sjövall, O., Salminen, S. Removal of the cyanobacterial toxin microcystin-LR by human probiotics. *Toxicon.* 2005; **46**:111-114.
86. Naskar, A., Guha, A.K., Mukherjee, M., Ray, L.,. Adsorption of nickel onto *Bacillus cereus* M116:

A mechanistic approach. *Sep. Sci. Technol.* 2016; **51**:427-438.

87. Nithya, C., Gnanalakshmi, B., Pandian, S.K. Assessment and characterization of heavy metal resistance in Palk Bay sediment bacteria. *Mar. Environ. Res.* 2011; **71**:283-294.
88. Nordberg, G.F., Nogawa, K., Nordberg, M., Friberg, L.: Cadmium. In: *Handbook of the toxicology of metals.* (Nordberg, G.F., Fowler, B.F., Nordberg, M., Friberg, L., eds). Amsterdam, Netherlands: Elsevier, 2007; pp 445–486.
89. Nordberg, M., Nordberg, G. On the role of metallothionein in cadmium induced renal toxicity. *Experientia Suppl.* 1987; **52**:669–675.
90. Nordberg, M., Nordberg, G. Toxicological aspects of metallothionein. *Cell. Mol. Biol.* 2000; **46**:451– 463.
91. Oaikhena, E.E., Makaije, D.B., Denwe, S.D., Namadi, M.M., Haroun, A.A. Bioremediation potentials of heavy metal tolerant bacteria isolated from petroleum refinery effluent. *Am. J. Environ. Protect.* 2016; **5**:29-34.
92. Ogunnusi, T.A., Oyetunji, O.A. Isolation of indigenous microorganisms from soil contaminated with metal scraps for the uptake of selected heavy metals in constituted growth media. *Afr. J. Microbiol. Res.* 2017; **11**:1643-1648.
93. Oller, A.R., Costa, M., Oberdörster, G.Carcinogenicity assessment of selected nickel compounds. Toxicol. *Appl. Pharmacol.* 1997; **143**:152-166.
94. Ottemann, K.M., Miller, J.F. Roles for motility in bacterial-host interactions. *Mol. Microbiol.* 1997; **24**:1109-1117.
95. Özdemir, S., Kýlýnc¸ E., Poli, A., Nicolaus, B.Biosorption of heavy metals ($Cd^{2+}$,$Cu^{2+}$, $Co^{2+}$, and $Mn^{2+}$) by thermophilic bacteria, *Geobacillusthermantarcticus* and *Anoxybacillusamylolyticus*: equilibrium and kinetic studies. *Bioremed. J.* 2013; **17**:86–96.
96. Pan, R., Cao, L., Zhang, R. Combined effects of Cu, Cd, Pb and Zn on the growth and uptake of consortium of Cu-resistant *Penicillium* sp. A1 and Cd-resistant *Fusarium* sp. A19. *J. Hazard. Mater.* 2009; **171**:761-766.
97. Patra, R.C., Rautray, A.K., Swarup, D. Oxidative stress in lead and cadmium toxicity and its amelioration. *Vet. Med. Int.***2011**, 1-9.
98. Priyalaxmi, R., Murugan, A., Raja, P., Raj, K.D. Bioremediation of cadmium by *Bacillus safensis* (JX126862), a marine bacterium isolated from mangrove sediments. Int. J. Curr. Microbiol. *Appl. Sci.* 2014; **3**:326-335.
99. Rajbanshi, A. Study on Heavy Metal Resistant Bacteria in Guheswori Sewage Treatment Plant. *Our Nat.*2008; **6**:52-57.
100. Rani, A., Kumar, A., Lal, A., Pant, M. Cellular mechanisms of cadmium-induced toxicity: a review. *Int. J. Environ. Health Res.* 2014; **24**:378-399.
101. Rathinam, A., Maharshi, B., Janardhanan, S.K.,Jonnalagadda, R.R., Nair, B.U.Biosorption of cadmium metal ion from simulated wastewaters using *Hypneavalentiae* biomass: a kinetic and thermodynamic study. *Bioresour. Technol.* 2010; **101**:1466–1470.
102. Saleem, M., Pirzada, T., Qadeer, R. Sorption of acid violet 17 and direct red 80 dyes on cotton fiber from aqueous solutions. *Colloids Surf. A Physicochem.Eng. Asp.* 2007; **292**:246–250.
103. Salman, A.A.Biosorption of Ni (II) by *Bacillus* sp. Isolated from Desert-Maranjab Soil. *J. Biol. Environ. Sci.* 2014; **8**:87-94
104. Sari, A., Mendil, D., Tuzen, M., Soylak, M.Biosorption of Cd (II) and Cr (III) from aqueous solution by moss (*Hylocomiumsplendens*) biomass: Equilibrium, kinetic and thermodynamic studies. *Chem. Eng. J.*2008; **144**:1–9.
105. Sari, A., Tuzen, M.Biosorption of cadmium (II) from aqueous solution by red algae (*Ceramiumvirgatum*): equilibrium, kinetic and thermodynamic studies. *J. Hazard. Mater.* 2008; **157**:448–454.
106. Seilkop, S.K., Oller, A.R.Respiratory cancer risks associated with low-level nickel exposure: an integrated assessment based on animal, epidemiological, and mechanistic data. *Regul. Toxicol. Pharmacol.* 2003; **37**:173-190
107. Shameer, S.Biosorption of lead, copper and cadmium using the extracellular polysaccharides (EPS) of *Bacillus* sp., from solar salterns. *3 Biotech* 2016; **6**:1-10.
108. Shoeb, E., Ahmed, N., Warner, P. J., Morgan, S., Azim, M. Identification of a unique mechanism of tolerance against nickel in *Bacilluscereus* isolated from heavy metal contaminated sites. *Internet J. Microbiol.* 2010; **9**:1-7.
109. Singh, S., Kashyap, N., Singla, S., Bhadrecha, P., Kaur, P. Bioremediation of heavy metals by employing resistant microbial isolates from agricultural soil irrigated with industrial waste water. *Oriental J. Chem.* 2015; **31**:357-361.
110. Song, S., Oh, S., Lim, K.T.*Lactobacillusplantarum* L67 glycoprotein protects against cadmium chloride toxicity in RAW 264.7 cells. *J. Dairy Sci.* 2016; **99**:1812-1821.
111. Stefanescu, I.A. Bioaccumulation of heavy metals by *Bacillusmegaterium* from phosphogypsum waste. *Sci. Stud. Res. Chem. Chem. Eng., Biotechnol. Food Ind.* 2015; **16**(1):93-97.
112. Suh, H.H., Lee, M.H., Kim, H.S., Park, C.S.,

Yoon, B.D.Bioflocculant production from *Bacillus* sp. A56. *Korean J. Appl. Microbiol. Biotechnol.* 1993; **21**:486–493.

113. Sulaymon, A.H., Mohammed, A.A., Al-Musawi, T.J. Competitive biosorptionoflead, cadmium, copper, and arsenic ions using algae. *Environ. Sci. Pollut. Res. Int.* 2013; **20**:3011–3023.
114. Syed, S., Chinthala, P. Heavy metal detoxification by different *Bacillus* species isolated from solar salterns. *Scientifica*, 2015; 1-8.
115. Taran, M., Sisakhtnezhad, S., Azin, T. Biological removal of nickel (II) by *Bacillus* sp. KL1 in different conditions: optimization by Taguchi statistical approach. *Polish J. Chem. Tech.* 2015; **17**:29-32.
116. Thijssen, S., Cuypers, A., Maringwa, J., Smeets, K., Horemans, N., Lambrichts, I., Van Kerkhove, E. Low cadmium exposure triggers a biphasic oxidative stress response in mice kidneys. *Toxicol.* 2007; **236**:29–41.
117. Todar, K. The Good, the Bad and the Deadly, firsted. Wyoming, USA. 2004.
118. Tzirogiannis, K.N., Panoutsopoulos, G.I., Demonakou, M.D., Hereti, R.I., Alexandropoulou, K.N., Basayannis, A.C., Mykoniatis, M.G. Time course of cadmium-induced acute hepatotoxicity in the rat liver: the role of apoptosis. *Arch. Toxicol.*2003;77:694 –701.
119. Uthra, K., Kadirvelu, K.Biosorption of nickel using mixed cultures of *Pseudomonas aeruginosa*and *Bacillus subtilis. Def. Life Sci. J.* 2017; **2**:442-447.
120. Valko, M., Morris, H., Cronin, M.T.D. Metals, toxicity and oxidative stress. *Curr. Med. Chem.* 2005; **12**:1161–1208.
121. Vijayadeep, C., Sastry, P.S. Effect of heavy metal uptake by *E. coli* and *Bacillus*sps. *J. Bioremed. Biodeg.* 2014; **5**:1-3.
122. Vijayaraghavan, K., Yun, Y.S. Bacterial biosorbents and biosorption. *Biotechnol. Adv.* 2008; **26**:266 –291.
123. Vimala, R., Das, N.Biosorption of cadmium (II) and lead (II) from aqueous solutions using mushrooms: a comparative study. *J. Hazard. Mater.* 2009; **168**:376–382.
124. Wu, G., Xiao, X., Feng, P., Xie, F., Yu, Z., Yuan, W., Liu, P., Li, X. Gut remediation: a potential approach to reducing chromium accumulation using *Lactobacillusplantarum* TW1-1. *Sci. Rep.* 2017; **7**:1-12.
125. Xiao, X., Luo, S., Zeng, G., Wei, W., Wan, Y., Chen, L., Guo, H., Cao, Z., Yang, L., Chen, J., Xi,Q.Biosorption of cadmium by endophytic fungus (EF) *Microsphaeropsis* sp. LSE10 isolated from cadmium hyperaccumulator*Solanumnigrum* L. *Bioresour. Technol.* 2010; **101**:1668–1674.
126. Yan, G., Viraraghavan, T. Heavy-metal removal from aqueous solution by fungus *Mucorrouxii*. *Water Res.* 2003; **37**:4486–4496.
127. Zhai, Q., Wang, G., Zhao, J., Liu, X., Tian, F., Zhang, H., Chen, W. Protective effects of Lactobacillus plantarum CCFM8610 against acute cadmium toxicity in mice. *Appl. Environ. Microbiol.* 2013; **79**:1508-1515.
128. Zhai, Q., Xiao, Y., Zhao, J., Tian, F., Zhang, H., Narbad, A., Chen, W. Identification of key proteins and pathways in cadmium tolerance of *Lactobacillusplantarum* strains by proteomic analysis. *Sci. Rep.* 2017; **7**:1182.
129. Zhang, J., Yang, T., Wang, H., Yang, K. Optimization of process variables by dried *Bacilluscereus* for biosorption of nickel (II) using response surface method. *Desalin. Water Treat.* 2016; **57**:16096-16103.
130. Zhang, Y., Du, R., Wang, L., Zhang, H. The antioxidative effects of probiotic *Lactobacilluscasei* Zhang on the hyperlipidemic rats. *Eur. Food Res. Technol.* 2010; **231**:151–158.
131. Zhou, W., Wang, J., Shen, B., Hou, W., Zhang, Y.Biosorption of copper (II) and cadmium (II) by a novel exopolysaccharide secreted from deep-sea mesophilic bacterium. *Colloids Surf. B Biointerfaces* 2009; **72**:295–302.