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Application of Phytoremediation to Reduce Environmental Pollution of Copper Smelting and Refinery Factories: a Review

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Abstract

Copper smelting and refinery factories are the final stages of a pyrometallurgical processing chain, and they cause many environmental challenges around the world. One of the most common environmental problems of these factories is toxic emissions. These toxic gases have harmful effects on the vegetation, animal species, soils, and water resources around the factories. Phytoremediation can play an important role in the reduction of the adverse effects of environmental pollutions arising from copper smelting and refinery factories. In this paper, we first discuss different types of pollutions caused by copper metallurgical factories, and present the main research approaches and studies conducted on these factories. In the second part, we provide a summary and comparison of different remediation technologies used to reduce the environmental pollutions of these factories. Besides, the advantages and disadvantages of each method is also investigated. In the third part, we review the different aspects of the phytoremediation including the effective mechanisms, different types of plants, application environments, and the effective factors. The next part includes the selection of suitable plants for the phytoremediation process applied for copper metallurgical factories and investigation of the native and cultivated hyperaccumulator plants. In addition, different efficiency indices are introduced for evaluating the phytoremediation efficiency and selecting an appropriate hyperaccumulator plant. At the final stage, some appropriate plant species for various types of phytoremediation are introduced. The effects of different environmental stresses and the possibilities of integrating phytoremediation with other remediation technologies as well as the advantages and disadvantages of phytoremediation are eventually investigated.

1. Introduction

The elevated concentration of toxic elements in plant, soil, water, and human body is a global environmental concern. Toxic elements can be dispersed to the environment in the form of polluted dust or suspended particles (Chen et al., 2014; Lu et al., 2014; Zheng et al.). Heavy metals released from industrial factories are accumulated in the soil and plant organs, and finally are transferred to the food chain (Kabata-Pendias & Mukherjee, 2007). The most important soil pollutants are Cu, Zn, Pb, Cd, As, Mo, Cr, Ti, Hg, Ni, Sb, and Se (Martin & McCutcheon, 1998). Investigation of the trace elements in the soil and plants related to the dust emitted from a factory is becoming a substantial research subject regarding the concentration type, source identification, spatial distribution, and remediation processes (Atiemo et al., 2012; Chen et al., 2014;

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Gunawardana et al., 2012; Huang et al., 2014; Liu et al., 2014; Qiao et al., 2014; Yoshinaga et al., 2014; Žibret et al., 2013). Industrial processes, especially mining activities such as smelting and refinery factories, create significant environmental problems (Ettler, 2016). Smelting and refinery factories produce massive quantities of toxic metals that threaten the human health and urban environmental quality (Charlesworth et al., 2011; Shi et al., 2013; X. Hu et al., 2011). In the absence of monitoring and controlling technologies in the smelting and refinery factories, the trace elements are eventually evaporated from ore materials and released to the atmosphere (Pacyna & Pacyna, 2002). For many years, the pyrometallurgical extraction process has raised some critical environmental concerns. Hydrometallurgy, as an alternative technique, has not had enough efficiency and recovery. Therefore, despite their massive capital investment, the environmental concerns and their intensive energy consumption, these smelting and refinery factories are still operating (Parameswaran et al., 2018).

Copper is one of the most exploited minerals, and mining of copper ore causes several multi-element environmental pollutions. The smelting processes of copper extraction emit large quantities of SO_2 and metallic ferrous dust. These contaminated dusts are scattered downwind of the chimney and creates topsoil trace metal acidification (Ayres & Ayres, 2002; Kozlov & Zvereva, 2007). The soils in the surrounding areas of the smelting and refinery factories are mostly contaminated by toxic metals. Cleaning these contaminations and reclaiming such damaged areas are among the most important issues related to these factories.

There are a wide range of remediation technologies implemented in the environmental decontamination. Over the past years, diverse technologies have been used for this purpose. The most critical point is that an efficient and sustainable remediation method, economically and operationally, requires a critical understanding of the factory processes and the contamination characteristics (Lianwen Liu et al., 2018). Due to technical and financial complications, the remediation of lands affected by smelting factories has become a challenging task in the environmental engineering. Furthermore, many scientists have investigated the application of different remediation techniques such as neutralization of the soil, vetrification, replacement, isolation, and immobilization around the factories (Bade et al., 2012; Chang et al., 2016).The employment of various conventional remediation methods faces several deficiencies and may create some hazards (Khalid et al., 2017). Chemical and physical remediation techniques are often efficient but most of them are time-consuming, costly, and environmentally destructive. Therefore, in the recent years, many attempts have been made on the design and implementation of the new technologies without leaving adverse impacts on the soil fertility and biological diversity (Singh & Ward, 2004).

Phytoremediation is a green and eco-friendly technology, which is economically cost-effective in terms of energy consumption. This technology includes the application of specific plant species and related microorganisms for remediation and stabilization of toxic metals (Golubev, 2011). Besides, phytoremediation allows the creation of appropriate visual landscapes as well as the pleasant public feeling (Ali et al., 2013). One of the essential advantages of the phytoremediation process against other technologies is that it can simultaneously remediate air pollutants from the factory outlet dust, contaminants absorbed into the soil, and also the groundwater pollution.

In the current paper, we review the different types and aspects of the environmental impacts of copper smelting and refinery factories, and present some of the most important research works in this regard and the scientific and technical approaches used in this field. In the following, different cleaning methods that can be used in the environmental protection related to these factories are compared and the advantages and disadvantages of each one are investigated. Then the technology of phytoremediation is introduced as a low cost, efficient, and eco-friendly technology, and its various aspects are examined. Typical application environments for phytoremediation and its various mechanisms, different types of plants, selection of suitable plants, and evaluation of the efficiency are investigated. Finally, the factors affecting the phytoremediation method and its advantages and disadvantages as well as the issue of combining this with other remediation technologies are investigated.

2. Environmental impacts of copper smelting factories

Mining operation and copper smelting factories cause a lot of environmental pollutions such as air pollution, disposal of smelting muds, soil contamination, and leakage into the groundwater. The contamination of soils and plants by dust particles released from copper smelting factories is the most important problem associated with such factories. For example, Table 1 presents the bulk chemical composition of a Cu smelter dust in Africa, and shows that the copper, iron, and sulfur pollutants are very high in the smelter dust.

Table 1. Bulk chemical composition of a Cu smelter dust in Africa (Vitkova et al., 2011).

Element	mg/kg	Element	mg/kg
Al	9715	Mg	4845
As	2786	Na	2074
Bi	15035	Ni	576
Ca	10805	Pb	2156
Cd	195	Si	42626
Co	992	Sn	1228
Cu	272745	Zn	2137
Fe	193915	C_{Total}	1446
K	6647	S_{Total}	85000

The plants and soils around a smelting and refinery factory are in the danger of contamination and should be monitored continually. Table 2 presents normal and toxic concentrations of trace metals in plants and soils. This table also presents the global average and critical concentrations of six major heavy metals (HMs) from different sources. The adsorption quantity in different types of soils and plants and also the competitive absorption between different heavy metals can be found in the literature (see Kabata-Pendias, 2010, for example). Elevated concentrations of pollutants near the smelting and refinery factories raise many concerns about the soils and plants. In addition, these pollutants can move down to the groundwater resources. Table 2 can be a guide to determine the contaminated soils and plants near the smelting and refinery factories of copper.

Table 2. Comparison of toxic and normal concentrations of trace metals (mg/kg or µgr/gr or ppm) in plants and soils.

	Plants						
Heavy metal	**Cu**	**Zn**	**Pb**	**As**	**Cd**	**Ni**	**Reference**
Normal amount in plants	5-20	1-400	0.2-20	0.02-7	0.1-2.4	0.02-5	(Agyarko et al., 2010)
Sufficient or normal range in mature leaves	5-30	27-150	5-10	1-1.7	0.05-0.2	0.1-5	(Kabata-Pendias, 2010)
Excessive or toxic Concentrations in plant leaves	20-100	100-400	30-300	5-20	5-30	10-100	(Agyarko et al., 2010; Kabata-Pendias, 2010)
	Soils						
Heavy metal	**Cu**	**Zn**	**Pb**	**As**	**Cd**	**Ni**	**Reference**
Critical Level	30	50	10	5	0.06	40	(Lindsay, 1979)
Europe's average	17.30	68.1	32	11.60	0.28	37	(Kabata-Pendias, 2010)
World's average	38.90	70	27	6.83	0.41	29	(Kabata-Pendias, 2010)
World average (uncontaminated soils)	25.8	59.8	29.2	11.3	0.6	33.7	(Bowen et al., 1982)
Average worldwide soil	34	36	47	13.75	.5	-	(McBride, 1994)
Crustal abundance	28	67	17	4.8	0.09	-	(Rudnick & Gao, 2003)
Critical concentration	50-125	300	100	-	3	50	(Cicek & Koparal, 2004)

Many rural and agricultural areas around the world are located near the copper smelting and refinery factories. The soil of such contaminated areas is often acidic and contains heavy metals. Soil acidification reduces the fertility and biodiversity (Wang et al., 2017). In addition, water bodies and animals around these factories are endangered. Figure. 1 schematically illustrates the pollution as a result of a copper smelting and refinery factory. It is a combined process, and the soil, plants, animals and water have a reciprocal effect to each other.

Depending on the type, texture, and permeability of surface soils, acidic rains and heavy metals can penetrate in the soils and move down to the groundwater flow system. The depth to the groundwater table and the soil heavy metal potential should be measured continuously near these factories.

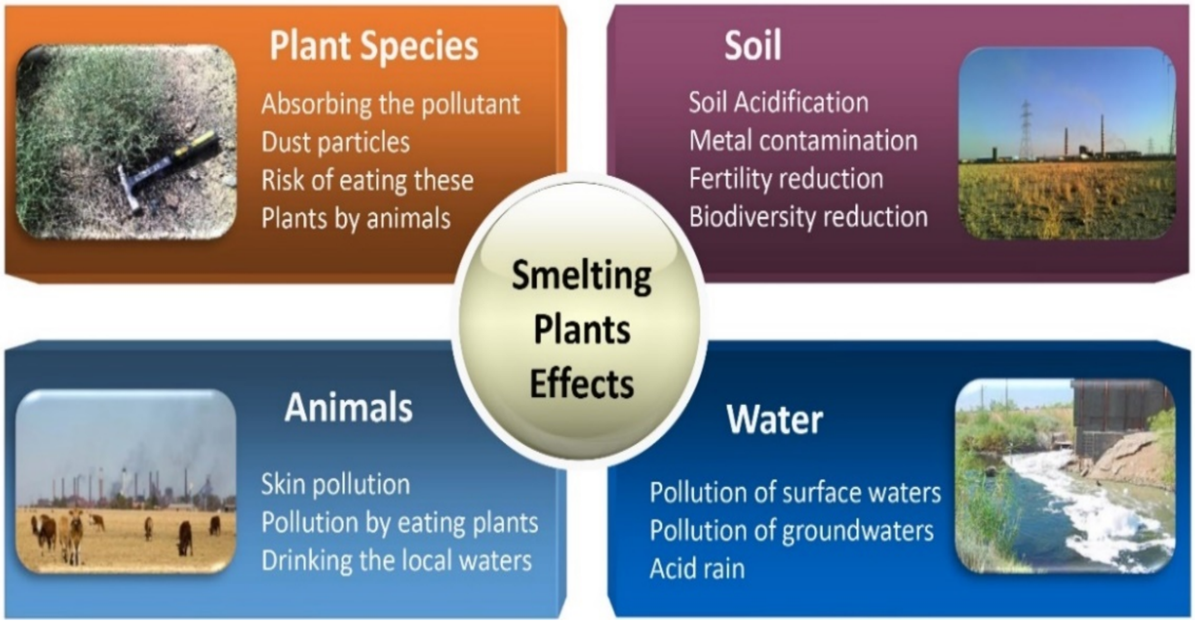

Figure 1. A general schematic representation of pollutant types resulting from copper smelting and refinery factories.

The environmental situation of copper smelting and refinery factories varies across the world. Table 3 provides a list of the world's most important copper smelting and refinery factories. The concentration of pollutants at different distances from the factory and at various depths of the soil profile are also presented. This concentration of pollutants depends on the soil type, wind direction, climate condition, and dust concentration. The general expectation is the decrease of concentration with increasing distance from the factories. However, in some regions around the world, the concentration of HMs is much higher in the far lands from the source than those regions located in nearby. For example, Arvay et al. (2017) have investigated the environmental pollutions caused by an abandoned mine and smelting factory in Slovakia. They reported that the spatial dispersion of mercury in four different ecosystems was not related to the distance from the factory.

Many research works have been conducted covering the different aspects of the pollution caused by the copper smelting and refinery factories. Mineralogy of the soil and the effect of soil type on chemical transportation are noteworthy (Bergstrom et al., 2011; Chopin & Alloway, 2007; Lahori et al., 2017; Ling Liu et al., 2010; Shukurov et al., 2014). Multivariate statistical methods have also been applied to investigate soil, plants, and water pollution during the production process in smelting and refinery factories (de la Campa et al., 2015; Demková et al., 2017; Kříbek et al., 2016; Shen et al., 2017; Wang et al.). Statistical methods play a crucial role in the study of environmental problems of the smelting and refinery factories. They are highly useful in determining the anthropogenic or natural source elements. It is also useful to predict the volume and extent of the contamination. Some other environmental assessment methods have been widely used such as pollution indices. The contamination factor (CF), enrichment factor (EF), contamination Intensity (Igeo), and potential ecological risk factor (Ei) are indices of the assessment of soil pollution (Árvay et al., 2017; Doyle et al., 2003; Rachwał et al., 2017; Serbula et al., 2014; Zhan et al., 2014). Several other studies have been conducted to examine the effect of these factories on the surrounding environment. Some studies have applied remote sensing methods to map the contaminated areas, precisely detect polluted parts, and determine the volume and extent of the pollution zones (Kalabin et al., 2014; Pryce & Abrams, 2010; Rastmanesh et al., 2010). Also multi-criteria decision-making methods (MCDM) have been widely used for environmental management and assessment of Cu content in the soils around these factories (Nikolić et al., 2009; Đ. Nikolić et al., 2011; Rezaei et al., 2015).

Table 3. The concentration of pollutants in topsoil at different distances from some of the most important copper smelting and refinery factories around the world (modified after (Anna et al., 2015)).

Smelter	Country	Distance (Km)	Depth (cm)	Cu (mg/kg)	Reference
Coniston	Canada	1.5 7.4 19.3 49.8	0-5	2007/1864 1425/1621 730/597 31/27	(Hutchinson & Whitby, 1977)
Severonickel	Russia	3-10 10-15 Over 20	0-15	246-4622 51-384 13-34	(Barcan & Kovnatsky, 1998)
Sarcheshmeh	Iran	2.55	0-5	479	(Khorasanipour & Aftabi, 2011)
			5-20	55.6	
			20-40	46.3	
		5	0-5	1220	
			5-20	104	
			20-40	111	
		15	0-5	124	
			5-20	120	
			20-40	143	
Khatoonabad	Iran	0.4	0-5	>10000	(Keshavarzi et al., 2015)
			5-20	6436	
		0.6	0-5	>10000	
			5-20	353	
		2.7	0-5	1278	
			5-20	3480	
		13	0-5	582	
Harjavalta	Finland	0.5 3 4 8	Humus layer/mineral soil 0-5	2304/259 1079/29.1 525/4.3 125/1.3	(Derome & Lindroos, 1998)
Sulitjelma	Norway	1 27 37	3-5	2500 10*BL 10	(Løbersli & Steinnes, 1988)
Las Ventanas I Chagres	Chile	2.6-8 13.5-26	0-20	113-384 62-89	(De Gregori et al., 2000)
Legnica	Poland	1 2 3 4	0-20	750-986 250-280 100-248 75-101	(Karczewska, 1996)
Glogow	Poland	0.5	0-20	Up to 1710	(Kabala & Singh, 2001; Karczewska, 1996)
		1	0-18	369	
		3		426	
		6	0-27	115	

The MCDM methods have also been used for ranking the pollution risks of every element in the soils and plants around the factories. Furthermore, isotopic studies have been extensively used to detect the source of trace elements in the vicinity of smelter factories (Deng et al., 2016; Ettler et al., 2006; Ratié et al., 2016; Ren et al., 2016). Examination of soil's organic matters (Hu et al., 2017; Ling Liu et al., 2010) has been used as a scientific method to investigate the contaminated soils around the factories and to determine the potential of contaminant transportation. A review of a number of these studies and applied methods is presented in Table 4.

Table 4. A review of some studies and main research approaches on pollution caused by smelting and refinery factories in the world.

Approach	Country	Smelting operation	Contaminant	Study technique	Reference
Multivariate statistics	Slovakia	Polymetallic	Cu, Zn, Pb, Cr, Cd, Ni, Co, Fe, Mn	Correlation coefficient & ANOVA test	(Demková et al., 2017)
	China	Cu smelter	Cu	t-test	(Wang et al., 2009)
	China	Pb/Zn smelter	Cd, Cu, Ni, Pb, and Zn	Clustering, PCA, Redundancy analysis (RDA)	(Shen et al., 2017)
	Spain	Cu smelter	Cu, As, Se, Bi, Cd, Pb	Factor analysis	(de la Campa et al., 2015)
	Namibia	Cu/Pb/Zn smelter	SO2, Cu, Pb, Zn, As	Correlation coefficient, PCA, dust dispersion modelling	(Kříbek et al., 2016)
Pollution indices	Slovakia	Hg, Cu smelting	Hg, Cu	Cf, Igeo, PER, BCF	(Árvay et al., 2017)
	Germany	Pb smelter	Fe, Mn, Ni, Cu, Zn, Cd, Pb	Cf, Igeo, PLI	(Rachwał et al., 2017)
	Serbia	Cu smelter	Cu, Zn, Pb, Mn	BCF, TF, BAC	(Serbula et al., 2014)
	China	Zn, Pb smelter	Cu, Cd, Pb, Zn	Igeo, ECF	(Zhan et al., 2014)
	Canada	Cu, Zn smelter	Cu, Zn, Ni, Pb, Cd, As	ENEV, CTV	(Doyle et al., 2003)
Mineralogy & soil fractions	China	Pb, Zn smelter	Pb, Cd, Cu, Zn	Lime combined with additives effect on immobilization	(Lahori et al., 2017)
	USA	Nine different Pb, Zn smelters	As, Cd, Pb, Zn	Size concentration relationships	(Bergstrom et al., 2011)
	Spain	Cu smelter	As, Cu, Zn, Pb	Soil particle characterization	(Chopin & Alloway, 2007)
	China	Cu smelter	Cu, Cd, Zn	Organic carbon and soil fractions	(Ling Liu et al., 2010)
	Uzbekistan	Cu, Zn, Pb smelters	Zn, Pc, Cd, Cu, Ni, Cr	Coupling geochemical, mineralogical and microbiological	(Shukurov et al., 2014)
Source detection	China	Pb/Zn smelter	As, Cd, Pb, Zn, Cu and Cr	Geostatistics	(Chaoyang et al, 2009)
Modeling of SO_2 emission	Serbia	Cu smelter	SO_2	Artificial neural networks (ANNs)	(Mihajlović et al., 2010)
Seasonal analysis	USA	Cu smelter	Sulfur oxides	Regional transport model (RTM)	(Nochumson & Williams, 1983)

Considering the above and the numerous environmental impacts of copper smelting and refinery factories that cause many adverse effects on water, soil, plants, and ecosystem resources in different regions around the world, it is necessary to find a cleaning method to reduce these destructive effects. Therefore, the next section introduces and compares the technologies that can be used to deal with these environmental challenges.

3. Comparison of Different Remediation Technologies

In general, the remediation methods related to smelting and refinery factories can be divided into five general categories that include the chemical, physical, electrical, biological, and thermal methods. Depending on the type of pollutant released from the factory and the extent and severity of the effects, one of them or a combination of these remediation methods can be used. Table 5 provides a summary of the types of smelting factories cleaning techniques, features, and advantages and disadvantages of each method. The comparison of various cleaning methods presented in Table 5 shows that the phytoremediation technology is the most effective technique for the remediation of pollutants in the vicinity of the smelting and refinery factories. Some researchers have investigated the application of different plants and phytoremediation technique in the copper contaminated areas (Boisson et al., 2016; Komárek et al., 2008; Lahori et al., 2017; Shutcha et al., 2010; Vyslouzilova et al., 2003). The selection of suitable plant species, finding native plant species, and studying the compatibility of the plant with the soil and climatic conditions around the factory are among the issues considered in the scientific investigations around the smelting and refinery factories.

In the next sections, different aspects of the phytoremediation technology are presented.

Different environments that can be used and diverse phytoremediation mechanisms are examined and evaluated. Various types of plants are introduced, and finally, different aspects of the selection of plant species and factors affecting the success of the process are discussed.

Table 5. A review of some technologies for the remediation of smelting and refinery factories pollutants.

Method	Mechanism	Situation	Workability	Cost (EUR/M3)	Efficiency	Time (Month)	Advantage	Limitation
Physical remediation								
Surface Capping	Impermeable material covering the contaminated site	In-situ	A	Med (100-220 €)	Low	Short (6-9 M)	No interaction with air and rain water	Does not remove heavy metal contamination
Encapsulation	Subsurface dams Separating the contaminated soils from clean parts	In-situ	C	High	Low	Med	Polluted zones cannot be extended	Subsurface dam material may have some risks
Landfilling	Removing polluted soil and transporting it to a the safe place	Ex-situ	C	Med (120-480 €)	High	Short (6-9 M)	Fast and secure cleanup	Necessity to an additional land for disposal
Soil Replacement	Replacing the polluted part with clean materials	Ex-situ	C	High	High	Short	Operative for highly polluted areas	Not cost-effective and hard to implement
Electrical remediation								
Electrokinetics	Removing trace element from soil and water using electric current	In-situ	C	High (210-420 €)	Med	Med (12-36 M)	Primary soil condition is maintained	Low permeability soil is required and the pH should be under control
Verification	Making vitreous material using high-temperature	In-situ	D	High	Low	Med	Appropriate for wide range of contaminants	High energy requirement
Chemical remediation								
Solidification	Transport the soil to a treatment facility and encapsulates it in an extruder	Ex-situ	D	High	Med	Long	High efficiency	High cost
Soil Washing	Extracting the soil and removing heavy metals by organic or inorganic extractants	Ex-situ	C	High (250-600 €)	High	Short (8-12 M)	Completely removes metals	Washing may have some environmental risks
Immobilization	Performs immobilizing modification to decrease the toxic element mobility	In-situ	A	Low	Med	Med	Wide range applicability and easy to perform	Necessity to external monitoring
Soil Flushing	Passing an extraction liquid through the soil	In-situ	B	Med	Med	Short	Low disturbance and simple to perform	Potential groundwater pollution

Table 5. Continuation

Thermal remediation								
Verification	High temperature can make vitreous materials	Ex-situ	D	High	Low	Short	Appropriate for a wide range of contaminants	High amount of energy is required, High cost
Biological remediation								
Microbial Remediation	Microorganisms have been used for remediation	In-situ	A	Med	Med	Med	Economical, low time of remediation	Microorganism type and soil category may affect the efficiency
Phyto-Remediation	Hyperaccumulator plants applied for remediation of contaminated soils and waters	In-situ	A	Low (20-50 €)	High	Med (12-36 M)	Low cost, ecofriendly, wide range of toxic metals	Time-consuming, depends on soil type and weathering condition

4. Phytoremediation Technology as a sustainable method

Phytoremediation includes various plant-based technologies, in which the natural plants are used to remediate the contaminated environments (Flathman & Lanza, 1998). The concept of applying plants for absorbing toxic metals and other compositions has been first introduced by Chaney (1983) but it has a background of about 300 years (Henry, 2000). In this method, it is emphasized to use non-edible plants that can absorb heavy metals. They are fast-growing, high biomass, resistant to the diseases, and compatible with the regional environmental situation (Ghosh & Singh, 2005).

4.1. Phytoremediation Mechanisms

Various processes of the phytoremediation significantly overlap with each other so that different processes occur during the plant accumulation. The plant accumulation comprises artificial methods and processes that lead to decomposition or immobility of contamination (Martin & McCutcheon, 1998). Figure 2 shows the general representation of the phytoremediation mechanism. A brief explanation of each of these mechanisms is provided below.

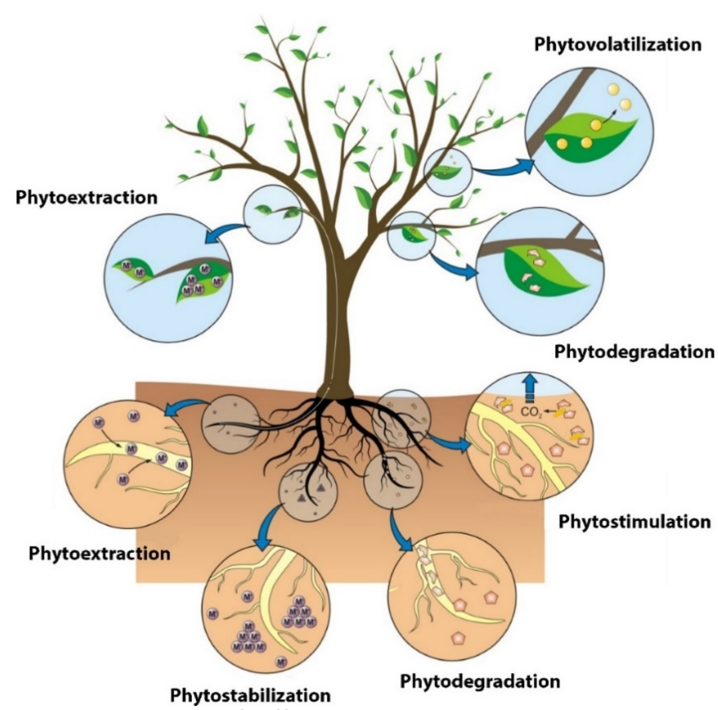

Figure 2. A general schematic view of different phytoremediation mechanisms (Favas et al., 2014)

4.1.1. Phytoextraction

Phytoextraction is the ability of the plant organs to remove the toxic elements, especially heavy metals, with the adsorption process. The contaminated plants can be harvested to remove or extract pollution (McIntyre, 2003). This method is useful for the remediation of the vast regions with shallow depths and moderate to low contamination levels. The plant adsorbs the metals from the soil and transfers them into the respiratory organs. Toxic elements are removed from the soil by plant harvesting. Amaranthus spinosus and Alternanthera species are capable for accumulating toxic elements in their leaves (Prasad, 2001). The conducted research works have shown that Canna x (a flowering plants), which is a decorative plant in rural landscapes, is a proper plant for the extraction of lead (Trampczynska et al., 2001). Sweet-scented geranium is also an efficient plant in the extraction of metals. In a greenhouse study within 14 days, young cuttings of Sweet-scented geranium extracted 90 milligrams lead, 27 milligram cadmium, and 19 milligram nickel. If this amount of absorption occurs in a farm situation, Sweet-scented geranium can remediate highly contaminated soils in less than ten years. A lead phytoremediation program using Sweet-scented geranium in 16 rounds with a density of 100 plants per square m within a year, removed 72 g lead in each square m. The total amount of extracted lead per hectare can be estimated, and it is about 1000 to 5000 kg. Therefore, if Sweet-scented geranium is planted in a soil that has a lead contamination of 1000 milligrams per kilograms soil, the plant can thoroughly remediate the contamination over eight years (Saxena et al., 1999).

Phytoextraction is the most well-known technology among all phytoremediation methods that can facilitate metallic contaminants removal from the soil. Application of Chelate increases the extraction of metals by plants. Chelates can increase the lead accumulation in Zea mays and Pisum sativum (Huang et al., 1997).

4.1.2. Rhizofiltration

Rhizofiltration is the application of plant root for absorption or even sedimentation of pollutants from contaminated waters (McIntyre, 2003). It is a low-cost technology for the remediation of surface and groundwater that contain slight but meaningful amounts of heavy metals including Cr, Pb, and Zn. In this process, the plants grown in a hydroponic system are moved into the contaminated waters to absorb the metals into their roots and respiratory organs. The appropriate plants for the remediation should be durable and store a significant amount of toxic elements. Moreover, they should be easily managed, have a low maintenance cost, and offer a sufficient amount of biomass. Besides, they should produce the least secondary waste materials (Dhir, 2016).

4.1.3. Phytostabilisation

Application of resistant plants for stabilization of contaminants through reducing the biological accessibility is called phytostabilisation. Traditional methods of reducing the metallic contaminants including immobilization or stabilization of metals in soil minimize the metal immigration but due to the soil erosion, the existence of metals always threatens human and animals. Heavy metal stabilization in contaminated soils through phytostabilisation prevents metal dispersion by wind and soil erosion, and ceases vertical migration of pollutants into groundwater systems. Compared to other remediation methods, the advantage of phytostabilisation is lower cost, less environmental pollution, easy to use equipment, and presenting aesthetics criteria. This method is a modified form of in-situ inactivation that the plant performance has a secondary role in soil remediation. In this method, the main goal is not removing the metallic pollutants but the plant can reduce the threats on human and environment by stabilizing the metals. Currently, two plant species, Schoenoplectus and Fescues, are available in the market to stabilize the soils contaminated by lead, copper, and zinc (Smith & Bradshaw, 1972). Phytostabilisation in fine-grained soils of high organic content is very effective but it is not suggested for highly contaminated soils because the plant cannot grow or survive in such environments.

4.1.4. Phytodegradation

Phytodegradation is the process of applying plants and microorganisms to reduce organic pollutants (McIntyre, 2003). This method includes the breakage of plant adsorbed organic molecules into simpler molecules. The plants that have oxygenase and reductase enzymes can conduct the breakage and conversion processes. Heavy metals are often in the form of ions, complexes, and unionized organic chelates. The solubility of these metals in the soil is controlled by the pH, metal content, ionic exchange capacity, organic carbon content, and redox potential (Eh). The solubility of metallic cations decreases as pH increases. Under an alkaline or nearly neutral pH, which is common in most of the soils, cationic metals are intensively adsorbed to the clay minerals. They can also be adsorbed to the soil oxides and hydroxides of Fe, Mn, and Al (Hakeem et al., 2014).

4.1.5. Phytovolatilisation

Phytovolatilisation is the process of applying the plants to evaporate the pollutants (McIntyre, 2003). In the recent years, numerous research works have been conducted on genetically modified plants to absorb the elemental form of toxic metals from the soil, and biological methods have been applied to convert them into the gas and release them to the atmosphere. This technology is a promising tool for remediation of the soil contaminated by selenium and mercury. The soils with high selenium contents are a serious problem all over the world. Some plants can evaporate selenium from their leaves. Lewis et al. (1966) have investigated these phenomena. The Matthoila plant family can release 40 g of gaseous compounds per day (Terry et al., 1992). Some aquatic plants, i.e. Typha latifolia, are also appropriate for phytoremediation of selenium. In the recent years, to volatilize mercury, several investigations have been carried out to introduce the bacterial mercuric reductase (Mer A) gene into aquatic plants. The plants that volatilize mercury are of genetically modified types. Arabidopsis Plants and Tabaco are modified by the Mer A and Mer B bacterial genes. These plants absorb elemental mercury and methyl mercury from the soil and then release them in the atmosphere through their leaves (Heaton et al., 1998). Table 6 presents a review on phytoremediation mechanisms and applications, as well as hyperaccumulator plants with pollutant type, applicable location, and stage purpose.

Table 6. A review on mechanisms and applications of phytoremediation and hyperaccumulator plants (modified after (Leung et al., 2013; Pinto et al., 2014)).

Mechanism	Stage purpose	Applicable location	Pollutants	Hyperaccumulator plants	Current situation
Phytoextraction (Phytoaccumulation) (Phytoabsorption) (Phytosequestration)	Absorption and extraction by plant	Soils, sediments, sludge	Cu, Zn, Pb, Cd, Cr, Hg, Co, Mo, Ni, Ag, Mn, Radioactive elements: $^{238,234}U$, ^{90}Sr, ^{239}Pu, ^{137}Cs,	Alyssum, Indian Mustard, Helianthus Annuus, Hybrid Poplar	Laboratory, experimental, and industrial scales
Rhizofiltration (Phytostimulation)	Absorption and extraction by plant’s root	Surface and ground water	Metals and radioactive elements	Helianthus annuus, Indian Mustard, Eichhornia Crassipes	Laboratory and experimental scales
Phytostabilisation (Phytoimmobilization)	Pollution suppression	Soils, sediments, sludge	Cu, Zn, Pb, As Cr, Cd, Hs	Indian Mustard, Eichhornia Crassipes, Microstegium Vimineum	Industrial scale
Phytodegradation (Phytotransformation)	Pollutants degradation	Soil, sediment, sludge, surface and ground waters	Organic compositions, chlorine solvents, phenols, herbicides, explosives	Algae, Eichhornia Crassipes, Willow, Taxodium Disticum	Industrial scale
Phytovolatilisation	Extraction of pollutants from the environment and releasing them into the atmosphere	ground water, soil, sediment, sludge	Some of the nonorganic elements: Se, Hg, As chlorine solvents	Populous, Alfalfa, Indian Mustard	experimental and industrial scales

4.2. Phytoremediation in Different Environments

One of the benefits of the phytoremediation technology, compared to other cleaning methods, is that it is not unique to a specific environment and can be used in different ecosystems like water, soil, and air. This is the advantage of phytoremediation treatment compared to other technologies that can be implemented in different environments. In the following, different environments where the phytoremediation method can be used are described.

4.2.1. Groundwater

Depending on the situation and selected regions, groundwater pollution can be controlled by the phytovolatilisation and phytodegradation methods. The extracted groundwater can be reused through the rhizofiltration process (Chandra et al., 2017; Pyatt, 2001).

4.2.2. Surface and Wastewater

Contamination of surface waters can be reduced by rhizofiltration or phytodegradation, and can be reused for agricultural applications (Pyatt, 2001).

4.2.3. Soil, Sediments, and Sludge

The phytodegradation, phytoextraction, and rhizofiltration technologies can be used for contaminated soils, sediments or sludge. Phytoextraction is the best method for remediation of the near-surface layer of contaminated soils in a wide area (Chandra et al., 2017).

4.2.4. Atmosphere

Most of the research works about plant accumulation have focused on liquid and solid contaminated environments, and there is less information regarding the application of phytoextraction on air pollution. The plant leaves directly absorb air pollutants. There are also several reports on the absorption of heavy metals by trees and oil pollutions by Chrysanthemum morifolium (Aksoy and Şahin, 1999; Chandra et al., 2017). Table 6 provides some of the hyperaccumulator plants and the related phytoremediation mechanism.

4.3. Different Kinds of Plants

Different plants show diverse behaviors when they are exposed to the contaminated environments (water, soil, and air). This varied behavior and performance lead to categorize different plants into four general groups. The plants in each category almost have a similar reaction against the pollutions. These four categories are explained in detail below.

4.3.1. Metal Repulsive Plants

Repulsive plants prevent the absorption of heavy metals or specific elements in respiratory parts (Ghosh & Singh, 2005; Martin & McCutcheon, 1998). Therefore, the concentration of these elements in plants tissues remains relatively low or constant. These plants mostly accumulate the contamination in their roots (Martin & McCutcheon, 1998).

4.3.2. Pollution Indicator Plants

These plants are categorized as tolerant plants (Burd et al., 2000; Martin & McCutcheon, 1998). Some species actively accumulate pollutants into their respiratory tissues. Generally, indicator plants absorb specific elements in proportion to their concentrations in the soil. Indicator plants do not necessarily need those elements for growth.

4.3.3. Accumulating Plants

Same as the previous category, these plants are also tolerant, and can accumulate pollutants into their respiratory tissues so that the concentration in these tissues is higher than the soil. Accumulating plants are capable of restoring high amounts of pollutions in their leaves, roots, and sprout (Baker & Brooks, 1989; Martin & McCutcheon, 1998). Absorption through roots depends on the type and amount of pollutant existing in the soil. Some plant species can absorb and accumulate high quantities of contaminants without revealing an obvious sign of poisoning. Some researchers have used the ratio of metal content in the respiratory tissues to the root for describing the plant strength and reaction to the highly contaminated soils. This ratio is greater than 1 for accumulating plants and less than 1 for repulsive plants. Many plants are naturally able to absorb the elements from the soil, and accumulate them in their roots and stem and then disperse them through the biological processes (Martin & McCutcheon, 1998).

4.4. Hyperaccumulator Plants

Hyperaccumulator was first introduced by Robinson et al., (1997). The hyperaccumulators contain abnormal and high metal contents in their plant solid matter. The ability of metal absorption in these species is 100 times higher than the non-hyperaccumulator species. For example, in a hyperaccumulator plant, the variation of element concentrations of Hg is more than 10 µg/g, and for Cd is more than 100 µg/g. For Zn and Ni, it is more than 10000 µg/g, and for Cu, Co, and Cr, it is more than 1000 µg/g. Until now, over 400 plant species from 45 families of hyperaccumulator plants have been reported. The most common type of these plants is related to nickel hyperaccumulators and the least common to cadmium (Martin & McCutcheon, 1998). Table 7 provides some of the hyperaccumulator plant species.

Table 7. Family of hyperaccumulator plants with maximum absorption of heavy metals (modified after (Lewis et al., 1966; Martin & McCutcheon, 1998))

Element (metal)	Number of species	Plant family
Cadmium	1	Matthiola
Cobalt	26	Antirrhinum Majus, Laurus Nobilis
Copper	24	Antirrhinum Majus, Cereal, Laurus Nobilis, Carex
Manganese	11	Aquifoliaceae, Glosbe,
Nickel	330	Violet, Flacourtiaceae, Spurges, Matthiola,
Selenium	19	Globes
Thallium	1	Matthiola
Zinc	16	Violet, Matthiola

Hyperaccumulator plants can be divided into the two broad categories of wild plants and cultivated plants. Each of these two categories has its own characteristics and advantages and disadvantages. The following two generic categories of hyperaccumulators are introduced and explained.

4.4.1. Wild or Native Hyperaccumulator Plants

Native plants are naturally found in plains and mountains, and have not been cultivated by humans. Depending on the soil, available water content, weathering conditions, temperature changes, and other environmental characteristics of each area, a number of special native plants that are compatible with these conditions grow naturally. These plants require less care than the cultivated plants, and they demonstrate greater resistance to the environmental conditions in the area.

The selection of native plants for cleaning the contaminated sites around the smelting and refinery factories may have various benefits. The adaptation of these plants to climatic and geological conditions has made it easier to maintain plants during the phytoremediation process. Sometimes, finding an appropriate superabsorbent plant for phytoremediation requires the examination of an area of as wide as about hundreds of km around the smelting and refining factory. Also it is necessary to sample several species from soils and plants in the area.

4.4.2. Cultivated Hyperaccumulator Plants

Cultivated plants are referred to as the kind of plants that do not grow by itself and require human planting and care. These plants are cultivated and developed for various purposes such as food resources and industrial uses. There are a variety of different species of cultivated plants that are planted and maintained for remediation purposes and used in various projects that require a high performance hyperaccumulator plant. For example, the Vetiver grass as one hyperaccumulator has been widely used in different aspects of the remediation, reclamation, and rehabilitation. Cultivated plants generally have better performance and higher HM absorption capacity than the native plants but may not be compatible with climatic conditions and soil and water characteristics of different areas.

4.5. Plant selection and phytoremediation efficiency

Choosing an appropriate plant for a phytoremediation process is one of the most important challenges in the success or failure of the project. There are two main strategies for selecting a hyperaccumulator plant for remediation around a copper smelting and refining factory. Native hyperaccumulators or cultivated plants are two main types that have been discussed. Each of these two options has its unique conditions and benefits that should be taken into consideration. Another critical issue in choosing plant species is taking into account the characteristics of the infected site. Features like concentration of the elements in the soil, as well as the type of the soil and its texture, are of the most important factors. It is also essential to pay attention to the plant type and its compatibility with different environmental and climatic conditions of the region. Environmental stress can also affect the efficiency of the phytoremediation process.

For selecting suitable plants, different algorithms have been presented. In the following section, three main indices are presented that can be used for evaluating the efficiency of the phytoremediation process. Metal accumulation index (MAI), GWRTAC index, and Chandra index are three main strategies that can be used for selecting an appropriate plant and generally evaluating the phytoremediation efficiency.

4.5.1. MAI Index

Metal accumulation index (MAI) is one of the best methods for evaluating the efficiency of the phytoremediation process, which has been presented by Liu et al. (2007) and further modified by Sharma (1999):

$$MAI = (1/N)\sum_{j=1}^{N} I_j \quad (1)$$

where N is the total number of metals analyzed and $I_j = x/\delta x$ represents the sub-index for variable j, obtained by dividing the mean value (x) of each metal by its standard deviation (δx). The greater the value of MAI index, the higher efficiency of the phytoremediation process.

4.5.2. GWRTAC Index

Another important factor involved for selecting a suitable plant is the time required for phytoremediation. The following equation presents a prediction for the time required for cleanup process (GWRTAC, 1998). The uptake rate should be divided by the mass of contaminant remaining in the soil:

$$k = U/Mo \quad (2)$$

where k is a first-order rate constant for uptake (yr^{-1}), U denotes the contaminant uptake rate (kg/yr), and Mo represents the initial mass of contamination (kg).Then an estimate for mass remaining at any time can be expressed by Eq. 3:

$$M = Mo.e^{-kt} \quad (3)$$

where M is the mass remaining (kg) and t represents the time (yr). Solving for the time required to achieve clean-up of a known action level:

$$t = -(\ln M/Mo)/k \quad (4)$$

where t is referred to as the time required for clean-up to action level (yr), M denotes the mass allowed at action level (kg), and Mo represents the initial mass of contaminant (kg).

4.5.3. Chandra Index

Chandra et al. (2017) have presented the following equation for estimating the efficiency of phytoremediation with a special accumulator plant:

$$M = Ad\rho_b\Delta C \quad (5)$$

where M is the amount of metal to be removed (mg), A represents the area of the contaminated site (m^2), D signifies the soil depth of contamination (m), ρ_b denotes the soil bulk density (km^{-3}), and ΔC is the expected contamination decrease (mg kg^{-1}).

$$t = \frac{M}{APB} \quad (6)$$

where t is the time (yr), P represents the metal concentration in plant tissue (mg kg^{-1}), and B denotes the annual plant biomass production (km^{-2}).

5. Factors Affecting Phytoremediation Performance

Similar to all biological processes, the performance of a phytoremediation method depends on the environmental factors. The most important factors affecting the phytoremediation performance are pH, organic matters, toxic matters, moisture content, temperature, ion exchange capacity, soil texture type, and soil permeability (Longley, 2007).

Another important factor affecting the phytoremediation performance is the environmental stress. Different types of environmental stress can influence the phytoremediation process. In the next sections, this critical issue is discussed.

5.1. Effect of Environmental Stress

As a general definition, stress is a kind of environmental factor that the plant cannot tolerate. In other words, stress is any change in the natural factors of the optimum growth state that reduces or adversely affects the plant growth and performance. In most cases, the stress is considered as the disturbance of the normal state of plant life and the variations and reactions that affect the performance in all levels. These variations are reversible or sometimes stable. Some of these environmental stresses affecting the plant performance are discussed below.

5.1.1. Salinity Stress

Salinity is a type of stress that exists in many locations around the world. Many types of research works have been conducted on this stress to develop the plants that are resistant to the salinity. Salinity is one of the most important stresses that reduce plant growth and production. The effect of salinity in a natural situation can be weak, moderate or intense. It is an important issue in arid and semi-arid areas. Many researchers have attempted to detect and modify the native plants that are resistant to salinity. An approach for using the salinity resistant plants is to investigate the mechanism of tolerance or strength from the plant physiological viewpoint. The plants are compared with each other for their morphological, physiological, and anatomical variations. Germination speed and percentage, plant appearance, variation of leaf surface, height, chlorophyll content, as well as the contents of Na, K, Ca, Cl, and concentration of soluble carbohydrates and proline ($C_5H_9NO_2$), leaf anatomy, and other characteristics under different salinities should be compared with each other to determine the critical limit of salinity resistance for each plant species (Ratié et al., 2016).

5.1.2. Drought Stress

Water is an important molecule for every physiological process in the plants, and it forms 80-90% of the plants biomass. If the water content is insufficient in a plant, the plant will experience a dehydration stage, which is technically called drought. Drought stress not only happens due to the lack of water but also takes place due to the conditions like low temperature or salinity. Therefore, molecular compositions greatly interfere in these processes and interactions. To overcome the drought stress, the plants have evolved a series of mechanisms. Molecular genetic aspects provide a proper response and compatibility for the plants against these stresses. Mutual effects between the plant and environment depend on intensity and duration of the drought period, as well as the stage of plant growth and its morphological/anatomical parameters (Ren et al., 2016).

5.1.3. Heavy Metals Stress

Heavy metals are characterized by specific gravity values of more than 5 g/cm^3. They comprise many elements of nature. Nevertheless, only a few of these toxic metals are found as soluble in biological situations that may be accessible for living cells. Some of these elements as micronutrients and trace metals (Cu, Zn, Cr, Ni, Fe, Co, Mo, Mn, V, W) are important for plant metabolism, and some can be toxic when their concentrations in the growth environment exceed the normal limit. Some other elements whose biological role is unknown and are highly toxic to the plant include Pb, Hg, As, Cd, Ag, Sb, and U.

5.1.4. Oxidative Stress

Oxygen has both positive and negative effects on the plants. Although oxygen is necessary for the plant growth, long time exposure to the oxygen damages the cells, and finally leads to plant death. This is due to the fact that the molecular form of the oxygen is reduced to the “reactivated oxygen species” (ROS), especially in the form of hydrogen peroxide (H_2O_2) and superoxide free radical anions (O^{2-}). These react with different cellular compositions and result in severe and irreparable harms that kill the cells. ROSs are largely produced in the plant cells through two structural ways. However, in a typical situation, the cellular reduction balance is preserved by the structural way that it is specially used for broad anti-oxidant mechanisms evolved in the destruction of ROSs (Ettler, 2016).

6. Advantages and Disadvantages of Phytoremediation

Obviously, phytoremediation, alike other remediation technologies, has some advantages and disadvantages. The important advantage of phytoremediation is the capability of affecting a broad range of organic and non-organic compositions. It can be performed in in-situ and ex-situ, and can reduce the quantity of residual waste. There is no need for an expensive equipment with highly experienced personnel. Compared to the common methods, phytoremediation can reduce the number of disturbed soils in in-situ remediation. Phytoremediation can reduce the expansion of pollution through water and air in the remediation process, and can also save the potential energy and convert it into the thermal energy.

There are some limitations and disadvantage for the phytoremediation technology. For example, it requires a long time for the remediation process and has limitations in some climatic conditions. Moreover, remediation is limited to the areas under the root coverage, and also there is the possibility of accumulating polluted components based on their categories and their characteristics. The possibility of polluted plants eaten by animals and insects and its probable effects on the food chain is another concern about the phytoremediation technology. Other shortcomings are its limitation to the areas with low pollution. Also the probable effect of non-native species on the ecosystem is another weakness of phytoremediation.

The above-mentioned limitations of the phytoremediation process have led the scientists to combine phytoremediation with other remediation technologies to reduce the deficiency and shortcomings and also enhance the performance of the method.

7. Combining and Enhancing Phytoremediation Performance

In the recent years, the scientists have tried to find useful approaches to increase the performance of the phytoremediation process. Accordingly, many combined methods have been developed, in which the phytoremediation technology is combined with some other remediation methods. Some of these methods such as the electro-kinetics remediation techniques have an individual cleaning performance. The simultaneous application of this method with the phytoremediation technology affects both systems. However, some others such as chemical addition do not have a separate remediation performance and can only accelerate the phytoremediation performance.

8. Conclusions and Perspectives

The smelting and refinery factories release toxic emissions and produce hazardous wastes. These factories are among the most polluted industries, and are responsible for the degradation of the surrounding waters, soils, plants, and animal ecosystems. The high capital investment and the failure of hydrometallurgical methods have led the refineries to continue the operation. The present study reviewed all research works on the environmental pollutions imposed by the smelting and refinery factories. Due to the importance and intensity of pollution, the main focus was on the copper smelters. Numerous smelting and refinery factories were investigated by collecting various studies conducted on different heavy metal pollution problems. The pollution intensity was compared with the global average values and limitations. Comprehensive statistics on the concentration of copper in different depths of the soil were collected for the most famous smelting and refinery factories around the world. The scientific approaches presented in these studies for investigation of this kind of factories were classified into six categories: multivariate statistics, pollution indices, mineralogy and soil Fractions, source detection, modeling of gas emission, and seasonal analysis. The details of the scientific methods were also presented for each category. Soil contamination is the major type of pollution around the smelting and refinery factories. Soil contamination can cause groundwater pollution and plant pollution, as well as animal species and indigenous and local inhabitants poisoning. Different technologies are used for the remediation of the soil around the smelting and refining factories, which vary in terms of mechanism, efficiency, price, time, and advantages and disadvantages. Also each one has its own specific application. Among these technologies, the phytoremediation method has a high priority due to its low cost, high environmental compatibility, aesthetics landscape, and a wide range of uses in the water, soil, wastes, and tailings. Plants are divided into three general categories based on their behavior against the pollutions: metal repulsive plants, pollution indicator plants, and accumulating plants. A significant advantage of the phytoremediation technology, which makes it an efficient way for the remediation of the contaminated sites, is the wide range of applications from the groundwater to the wastewater treatment, soil contamination, and also air pollutions. However, many factors such as climatic conditions, pH, temperature, moisture, and concentration of contaminants affect the performance of the phytoremediation process.

Five main mechanisms of the phytoremediation process including phytoextraction, rhizofiltration, phytostabilisation, phytodegradation, and phytovolatilisation were studied in details in the current research work. The fields of application, possible locations, type of pollutant, and state of the art of each division were investigated as well. Furthermore, upscaling from laboratory to real case was evaluated, and for each mechanism, a super-absorbent plant species was introduced. The selection of appropriate plant species like native wild species or alien hyperaccumulators depends on the range of contamination in each plant for specific metals. For this purpose, several plant species have been proposed in various studies, which have been collected and presented separately for each particular heavy metal. There are a diverse range of the native and the cultivated hyperaccumulator plants with a wide range of applications from slope stability to wastewater treatment that can be used to eliminate contamination from the smelting and refinery factories. The key point is that the selected plant should be highly resistant in various climatic conditions and environmental stresses and have a high capacity for accumulating heavy metals. Some kinds of hyperaccumulator plants in different phytoremediation mechanisms were introduced. Therefore, it is an appropriate alternative for dealing with the environmental challenges of the smelter factories. Some challenges can reduce the efficiency of the treatment process through phytoremediation. These challenges include susceptibility to climate conditions, concern about the consumption of the polluted plants by the animals, and its long-term performance. The environmental stresses including salinity, drought, heavy metal, and oxidation stress affect the phytoremediation process. In order to deal with such challenge, phytoremediation can be combined with other cleaning methods such as electrokinetics, nanotechnology, CO_2 injection, and addition of bacteria that increase the efficiency and performance of this approach.

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استفاده از روش گیاه پالایی در کاهش آلودگی‌های زیست محیطی کارخانه‌های ذوب و پالایش مس: یک مطالعه مروری

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چکیده:

کارخانه‌های ذوب و پالایش مس، آخرین حلقه از زنجیره تولید پیرومتالوژیکی فلز مس بوده و آلودگی‌های زیست محیطی بسیاری را در سرتاسر جهان ایجاد نموده‌اند. یکی از مشکلات زیست محیطی رایج این کارخانه‌ها، انتشار گازهای سمی است. این گازهای سمی، اثرات مخربی بر گیاهان، گونه‌های جانوری، خاک و منابع آبی اطراف کارخانه دارند. فرآیند گیاه پالایی، می‌تواند نقش بسیار مهمی در کاهش اثرات مخرب زیست محیطی این کارخانه‌ها داشته باشد. در پژوهش حاضر، در ابتدا انواع آلودگی‌های ناشی از کارخانه‌های ذوب و پالایش مس معرفی شده و رویکردهای تحقیقاتی اصلی و مطالعات انجام شده در این خصوص مورد بررسی قرار گرفته است. در بخش دوم به طور خلاصه انواع تکنولوژی‌های به کار رفته به منظور پاکسازی آلودگی‌های زیست محیطی این کارخانه‌ها، با یکدیگر مقایسه شده‌اند. بعلاوه، مزایا و معایب هر کدام از این تکنولوژی‌ها مورد بررسی قرار گرفته است. در بخش سوم، جنبه‌های مختلف تکنولوژی گیاه پالایی، شامل فرآیندهای مؤثر، تنوع گونه‌های گیاهی، محیط اجرا و فاکتورهای تأثیرگذار، مرور شده است. بخش بعدی، شامل نحوه انتخاب گیاهان مناسب به منظور استفاده در فرآیند گیاه پالایی در کارخانه‌های ذوب و پالایش مس است و گیاهان بومی و گیاهان دست کاشت مختلف معرفی گردیده‌اند. بعلاوه شاخص‌های مختلفی که به منظور سنجش کارایی فرآیند گیاه پالایی و همچنین انتخاب گیاه سوپر جاذب مناسب تا کنون ارائه شده، معرفی و مورد بررسی قرار گرفته است. در پایان برخی گونه‌های گیاهی مناسب به منظور استفاده در کارخانه‌های ذوب و پالایش مس معرفی شده و تأثیر تنش‌های محیطی مختلف و ترکیب روش گیاه پالایی با دیگر روش‌های پاکسازی مورد بررسی قرار گرفته و نقاط ضعف و قوت فرآیند گیاه پالایی تشریح شده است.

کلمات کلیدی: زیست بوم صنعتی، فناوری‌های پاکسازی، گیاهان سوپر جاذب دست کاشت، تنش‌های محیطی، کارخانه‌های متالوژیکی مس.