Chapter

Phytoremediation: An Ecological Solution for Decontamination of Polluted Urban Soils

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Abstract

Urbanization and industrialization are the main causes of increasing contaminated soils in cities all around the world. This leads to numerous abandoned lands, reduction in biodiversity, and thereby posing a serious health risk for urban inhabitants. The development of effective and ecological remediation approaches is necessary. Phytoremediation is well known as an ecological solution with good acceptation for remediation of contaminated soils. Since, urban soils are particularly characterized by their highly disturbed, heterogeneous and low fertility, the application of phytoremediation to rehabilitate contaminated soils in urban areas is until now very limited at the laboratory scale and even less at the field scale. In this context, we have to take into account all these parameters and precautions when it's application. The main objective of this chapter is to discuss how to take phytoremediation approaches from a proven technology to an accepted practice in an urban context. An overview of urban soil types is provided following phytoremediation's application for urban soils with the focus on inorganic and organic pollutants, to provide a frame of reference for the subsequent discussion on better utilization of phytoremediation. At last, we offer suggestion on how to gain greater acceptance for phytoremediation by urban inhabitants.

Keywords: phytoremediation, ecological solution, urban soils, social sciences, ecological garden

1. Introduction

Although occupied only a small (<3%) proportion of the Earth's terrestrial surface, urban soils provide a wide range of ecosystem services to inhabitants of cities [1]. In the current context of population growth and urbanization as well as rapid industrialization, urban soils have largely disappeared and polluted by different types of organic and inorganic pollutants. According to urban scholars, although there is an increase of the cultural levels and diverse with more various cities, urbanization however generally leads to a reduction in biodiversity and ecosystem quality. Over the last decade or more, urban gardening is privileged and growing trend in many cities all around the world. For this development, the inhabitants should be assured of that the land is clean and safe. It is urgent that urban soil remediation projects must be to encourage investments.

Conventional methods of soil decontamination possess disadvantages in forms of environmental cost and financial burden. This truth leads to the search of ecological technologies for restoration of urban soils. One such approach includes phytoremediation. Phytoremediation is a process that uses plant for biological treatment of both organic and inorganic from polluted soils in non-urban and urban areas. Operating costs are very low, ranging from $ 0.02 to 1.00 per m^3 of soil [2]. Phytoremediation is based on the use of plant species to extract, retain, immobilize or degrade pollutants in soils. This technique provides good recovery of soils contaminated with heavy metals, and petroleum hydrocarbons.

In the urban context, there are two challenges in attracting the application of phytoremediation for contaminated soils. First, how do make the application of this approach operate and effective? Second, how do inform and train professionals and also non-professionals of the remediation of the contaminated soils potential offered by phytoremediation approaches. This will encourage the use of an ecologically, viable and socially accepted depollution technique.

In this chapter, we will discuss how to take phytoremediation approaches from a proven technology to an accepted practice in the urban context. An overview of urban soil types is provided following phytoremediation's application for urban soils with the focus on inorganic and organic pollutants, to provide a frame of reference for the subsequent discussion on better utilization of phytoremediation. At last, we offer suggestion on how to gain greater acceptance for phytoremediation by urban inhabitant.

2. An overview of urban soil contaminations

2.1 Urban soil type

"Urban soils" could have several definitions according to scientific or technic domain considered. For World Reference Base for Soil Resources (WRB), urban soils are composed of "any material within two meters of the Earth's surface that is in contact with the atmosphere, excluding living organisms, areas with continuous ice not covered by other material, and water bodies deeper than two meters" [3]. The Morel and Schwartz team's works made it possible to complete the definition by adding that these soils are under strong human influence in the urban and suburban landscape [4–6]. These soils are called Technosols [3]. Their studies begin to be more and more important at the beginning of the 21st century with an exponential increase in the number of publications concerning urban soils (**Figure 1**). Indeed, before the 2000s, the urban soils were considered too disturbed, polluted and poor fertility. Nevertheless, with the ever-increasing population in the city and the growing public concern about environment and human health, the restoration or rehabilitation and remediation of these soils have become a priority. In the urban area, soil is a key issue, subject to very rapid changes in allocation and use (green space, gardens, peri-urban agriculture, urban and industrial activities). Soils provide many essential ecosystems services in urban area, such as carbon and mineral nutrients storage, biota's habitat, role in hydrologic cycle by reducing runoff and promoting infiltration, water supply and reduction of pollutant bioavailability.

The main characteristics of urban soils are strong vertical and horizontal spatial heterogeneity in terms of physical, chemical and biological properties [7]. This strong variability can be explained by differences in occupation and use, such as the soils supporting buildings and infrastructures, landscaping areas.

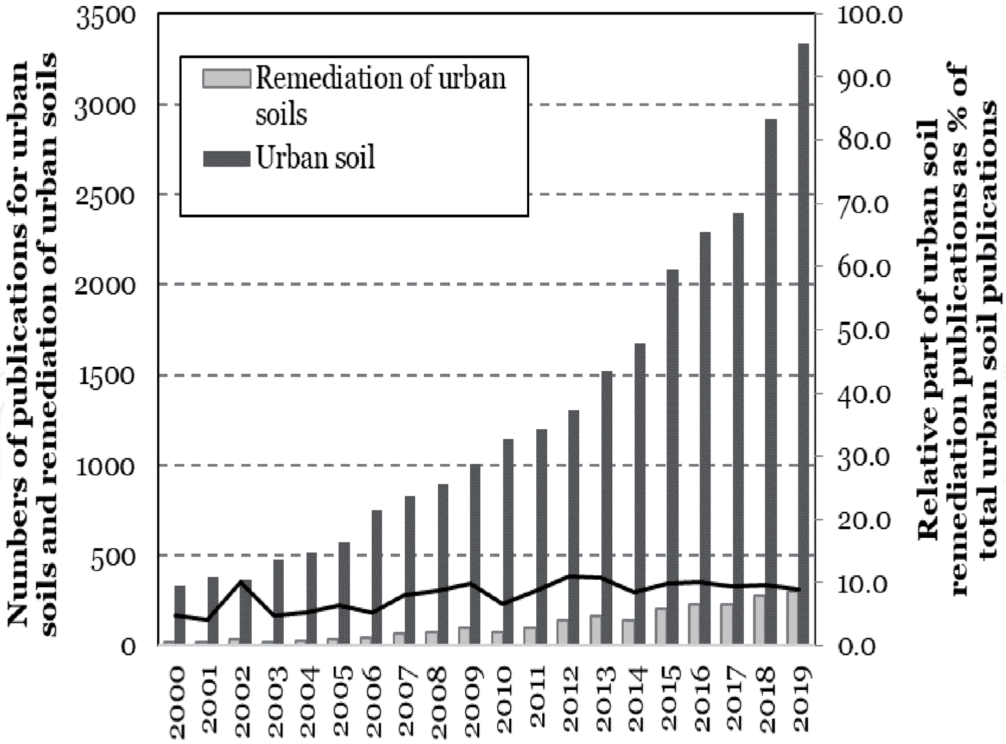

Figure 1.
Evolution of the number of annual scientific publications on soils (dark gray histogram) and urban soils (histogram light gray) in the international scientific literature over the period 2000–2019. Evolution of the relative share of publications on soil remediation urban is represented by the black curve, which is estimated as % of the total number of publications on urban soils. Bibliometrics on the state of scientific and technological knowledge on urban soils has been evaluated with two search engines: Web of Science and Medline, using these keywords "urban soil", "remediation", "restoration", "rehabilitation" with different combinations.

Various anthropogenic factors lead to a modification of the initial state of the soil in urban zones. Moreover, most of urban land are the new soils created through mixing, incorporation, and export of earthy materials, compaction or sealing. Unfortunately, the incorporation of these materials leads to frequent pollution of these soils. In general, urban soils display raised pH values due to addition of calcareous and other waste building materials.

2.2 Pollutant types in urban soil

Due to the human activities, urban soils are contaminated with various organic and inorganic pollutants. Among which, polycyclic aromatic hydrocarbons (PAH), pesticides, biphenyl-polychlorinated (PCB), metals, metalloids and radionuclides are the most abundant. Their presence in soil is undesirable due to their highly toxic and the environmental disturbances they create. Soils contain natural quantity of potentially toxic metals due to constitution of parent rock materials. Trace metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), zinc (Zn), copper (Cu), nickel (Ni) and some metalloids such as arsenic (As), Selenium (Se), manganese (Mn) are toxic for living organisms even at low concentration in soils. Whereas some trace metals such as zinc (Zn), copper (Cu), nickel (Ni) are vital elements for living organisms and their physiological properties (enzyme activators, electron transfer system in photosynthesis and respiration). Moreover, the presence of hydrocarbons and metals in soils affects negatively seed germination and plant growth [8], soil microbial community and activities [9], metabolic capacities of plants and microorganisms [10].

Nevertheless, since several decades, the anthropogenic origins of all the urbans pollutants are various and mainly attributed to (i) transport sources (traffic, vehicle emission, brake and tyre wear), (ii) commercial and industrial emissions (energy production, electronics, metallurgical and chemical industries, fuel combustion, incineration), (iii) domestic activities (construction and demolition, waste disposal, wastewater), and (iv) agricultural activities (application of fertilizers and pesticides, wastewater irrigation) [11].

Soil erosion and storm water runoff in urban areas are the main contributor to diffuse pollution according to the United States Environmental Protection Agency [12]. Moreover, the incorporation of calcareous and other waste building materials into urban soils are no negligible and several inorganic pollutants, especially trace metals, are being introduced into these soils leading their use dangerous for human health. Degradation of trace metals is not possible; therefore, they are accumulated and persist in the soil for many years. The concentration of various pollutants in rural and urban areas in France are presented in **Table 1**. We can see that the concentrations of the most of pollutants are superior in urban area than in rural area. These data confirm also the heterogeneity of these urban soils and are coherent with the concentrations of urban soils of other metropolises (USA, Spain, China, Ireland, Finland, Algeria, Nigeria and Iran) [7].

The review of the literature indicates that most scientific articles (>80%) focus on metals and little data are available on traditional or emerging organic pollutants that are now being detected. Many studies still need to be carried out to assess the impact of these pollutants on urban soils and consequently on ecosystem services provided by these soils, and more broadly on human health.

2.3 Ecological methods for restoration of contaminated urban soils

As seen earlier in Section 2.1, urban soils are much polluted. It is therefore necessary to treat them before any other use, be it for parks or gardens. Obviously, depending on the nature of the pollutants (organic or inorganic), their concentrations, and the soil physic-chemical properties, the appropriate technique will differ. Moreover, the reason for which monitoring will also be a criterion for the choice of operational staff. The remediation technics used for the depollution of contaminated site can be in situ or ex situ, on site or off site and biological, physical and chemical. They are often employed in combination with each other in order to optimize the system more efficiently and cost-effectively.

Ecological methods for soil remediation have received considerable interest in the last decade (**Figure 1**) and exhibit almost 10% of the publications on urban soils. This growing interest has several reasons such as potential cost savings compared to conventional non biological techniques and the benefit effects of this techniques on urban soil that are often polluted with a poor fertility. Ecological methods the most used in urban soils are phytoremediation, microbes-assisted-remediation, and amendment incorporation. Phytoremediation can be used in combination with this other technique.

Phytoremediation [10, 11] consists to use of plants to remediate and revegetate contaminated sites. Phytoremediation technique was first developed to clean up heavy metal(loid)s contaminated soils, thus, the first publications on the subject appears at the end of 1980s and beginning of the 2000s for urban soils. Phytoremediation is considered environmentally friendly, esthetically pleasing, non-invasive and cost-effective technology to clean up the sites with low-to-moderate levels of heavy metal(loid)s (see Section 2).

Amendment incorporation in urban soils corresponds mainly to organic amendment such as compost or biochar [12, 13]. In urban soils, this technique is used since 2000s for disturbed soils with poor structure and low levels of OM and fertility in order to improve the physical properties (such as bulk density, infiltration rate,

			Data acquired in mainly rural areas			Data acquired in mainly urban areas		
Family	**Name**	**Unit**	**Min**	**Med**	**Max**	**Min**	**Med**	**Max**
Trace metals	As	mg/kg	1.00	—	25.00	1.00	**8.80**	50.20
	Pb	mg/kg	2.20	**34.10**	91.50	5.30	**57.40**	650.00
	Zn	mg/kg	<5	**80.00**	275.00	13.00	**94.90**	2600.00
	Ni	mg/kg	<2	**31.00**	78.90	4.00	**15.00**	6200.00
	Hg	mg/kg	0.02	—	0.10	0.05	**0.20**	28.00
	Cd	mg/kg	<0.02	**0.16**	6.99	0.05	**0.43**	3.63
	Cr	mg/kg	<2	**66.30**	118.00	0.90	**21.00**	111.30
	Cu	mg/kg	<2	**12.80**	27.20	4.20	**27.00**	190.00

			Data acquired in mainly rural areas			Data acquired in mainly urban areas		
Family	**Name**	**Unit**	**Min**	**Med**	**Max**	**Min**	**Med**	**Max**
HAP	Naphtalene	mg/kg	0.00	**0.00**	1.03	0.01	**0.11**	11.00
	Acenaphtylene	mg/kg	0.00	**0.00**	0.53	0.01	**0.14**	15.00
	Acenaphtene	mg/kg	0.00	**0.00**	0.16	0.02	**0.16**	13.00
	Fluorene	mg/kg	0.00	**0.00**	0.25	0.01	**0.08**	6.40
	Phenanthrene	mg/kg	0.00	**0.01**	3.47	0.01	**0.12**	7.80
	Anthracene	mg/kg	0.00	**0.00**	0.56	0.02	**0.21**	33.00
	Fluoranthene	mg/kg	0.00	**0.01**	6.08	0.01	**0.12**	10.00
	Pyrene	mg/kg	0.00	**0.00**	4.37	0.01	**0.02**	0.64
	Benzo(a)anthracene	mg/kg	0.00	**0.00**	2.18	0.01	**0.05**	1.90
	Chrysene	mg/kg	0.00	**0.00**	4.14	0.02	**0.12**	10.00
	Benzo(b)anthracene	mg/kg	0.00	**0.00**	2.22	0.01	**0.02**	0.60
	Benzo(k)anthracene	mg/kg	0.00	**0.00**	1.46	0.01	**0.08**	16.00
	Benzo(a)pyrene	mg/kg	0.00	**0.00**	1.73	0.02	**0.17**	29.00
	Indeno(1, 2, 3-cd)pyrene	mg/kg	0.00	**0.00**	1.83	0.01	**0.05**	1.20
	Dibenzo(a,h) anthracane	mg/kg	0.00	**0.00**	1.13	0.01	**0.05**	0.70
	Benzo(g, h, i)perylene	mg/kg	0.00	**0.00**	1.53	0.01	**0.02**	12.00
	Σ 16 HAP	**mg/kg**	**0.13**	**0.16**	**31.67**	**0.28**	**1.56**	**167.31**
PCB	**Σ PCB**	**µg/kg**	**0.20**	**0.70**	**17404.20**	—	—	—
Dioxines/furanes	Σ Dioxines/furanes	**ng/kg**	24.75	**28.17**	2095.28	27.58	**162.70**	4678.40
Cyanure	Cyanure	mg/kg	—	—	—	0.10	**1.00**	6.10
Phenol	Indice phenol	mg/kg	—	—	—	0.01	**0.48**	86.00
Hydrocarbures	C_{10}, C_{40}	mg/kg	—	—	—	0.50	**20.00**	260.00

Table 1.
Concentration of organic and inorganic pollutants in rural and urban soils in France (values extracted from Ademe [13]).

hydraulic conductivity, water content, aggregate stability, and porosity) and function (such as water and nutrients available for plants, support for living organisms, etc.). Concerning contaminated urban soils, the studies on biochar has shown its ability to bind metals, decrease their mobility and bioavailability, stimulate microbial activity and promote soil revegetation and recovery (see Section 3.3).

Microbes-assisted-remediation [14] or bioremediation is a method involving the use of microorganisms to breakdown hazardous contaminants/pollutants to nontoxic or harmless forms. This technique was mainly used for organic pollutants. It can be also used for inorganic pollutant to stabilize metals or metalloids into soil or extract them when associated to phytotechnologies. Bioremediation techniques are mainly of two types: in situ (at the site of contamination) and ex-situ. Bioremediation presents several benefits such as economic viability, social acceptability, and eco-friendly (see Section 3.1).

3. Phytoremediation in urban context

3.1 Phytoremediation of inorganic pollutants

Inorganic pollutants which include heavy metals and metalloids are release into the environment due to human activities of industry, transportation and also urban activities. In order to remediate the soils polluted by inorganic pollutants, several conventional chemical and physical techniques have been used for decades; however, they are expensive and often hard to set-up. Recently, phytoremediation is admitted as an appropriate method using plants for the depollution of inorganic pollutants. The number of publications related to phytoremediation has only increased since the early 2000s with an average of 700 articles per over the last 5 years (source: Web of science) with 3–5% focused on urban soil. Moreover, 90% of these publications are related to phytoremediation of soils contaminated by trace metals and metalloids.

Phytoremediation of inorganic pollutants refers to phytoextraction, phytostabilization, phytovolatilization and rhizofiltration [14, 15]. Phytovolatilization (only for mercury and selenium) and rhizofiltration are still techniques with an experimental approach and mostly under controlled conditions unlike phytoextraction and phytostabilization which have been applied in the field, and most used to rehabilitate urban soils.

Phytostabilization consist to cover contaminated soil by plants either by seeding or planting. As a consequence, the biological, physical and chemical properties of the soils will be improved. The presence of vegetal cover, especially dense root system will permit to decrease the dispersion/mobilization of inorganic pollutants by promoting (i) water infiltration rather than runoff, (ii) evapotranspiration which will limit the percolation of water and thus the leaching of contaminants, and (iii) by retaining fine particles. Thus, plants will stabilize inorganic pollutants by accumulating them in the rhizosphere or into roots and will decrease their bioavailability. Phytostabilization, despite these many advantages (improvement of biological, physical and chemical qualities and consequently the increase in soil ecosystem services), is above all more a management strategy for polluted urban soils than a depollution technique since trace metals and metalloids remain in the soil. The application of amendments promotes the heavy metal stabilization in soils. Recently, aided phytostabilization have been used for remediation of urban soils [16–18]. This technique consists in the chemical stabilization of inorganic pollutants with the combined use of a wide range of soil amendments with a selected plant. This soil amendment can be natural mineral (phyllosilicates, zeolites, and oxides), organic substances, industrial or urban wastes and agriculture (manure, straw, and composts). This amendment will increase the soil pH and sorption capacity of soil rhizosphere (see Section 2.3).

Phytoextraction is based on the ability of plants to grow on contaminated soils, absorb inorganic pollutants by their roots and then transfer and accumulate them in significant quantities in their aerial organs (stem, leaves, and reproductive organs). The pollutant presented in soils must therefore be bioavailable for plants. Thus, the phytoremediation process will increase the fraction of metals bioavailable for plants depending on a combination between plant physiology, soil microorganisms (see Section 3.1), soil chemistry and the interaction between plant and microbes. There are many reviews that inventory these hyperaccumulators or high biomass accumulating plants used as a function of the major trace metals or metalloids they accumulate [14, 19, 20].

Moreover, in order to improve the efficiency of plants involved in phytoextraction process, many authors proposed the transfer of the hyperaccumulator phenotype from small and slow growing hyperaccumulator species to fast growing, high biomass-producing non-accumulator plants. Many genes involved in the acquisition, allocation and detoxification of metals come from bacteria and yeasts [21]. For example, some works on bioengineering have used plants capable of removing methyl-mercury from contaminated mining and urban soils [22], a strong neurotoxic agents, is biosynthesized in Hg-contaminated soils. To detoxify this compound, transgenic plants have been engineered to express modified bacterial genes *merB* and *merA*.

In the case of lead (Pb) which is one of the most trace metals presented in urban soils (see Section 2.2), the content of bioavailability lead in the soils is very low and it is difficult for plant to uptake them. Therefore the rehabilitation of soils polluted be lead is often difficulty. To overcome the problem, it is necessary to realize assisted phytoremediation [23]. This technique consists of adding to the soil various chemical compounds that can increase the availability of trace metals or metalloids in the soil solution. The chemical compounds used are generally aminopolycarboxylic acids (APCA), molecules chelating metal cations such as ethylenediamine tetraacetic acid (EDTA), nitrilotriacetic acid (NTA), hydroxyethylenediamine-tetraacetic acid (HEDTA) or diethylenepentaacetic acid (DTPA). Nevertheless, it has been shown that the aminopolycarboxylic acids can be toxic for some plants, microorganisms or nematodes. Meanwhile organic acids such as citric or oxalic acids which are less toxic can be used, but they are less effective in increasing the fraction of trace elements easily assimilated by plants. Moreover, transgenic plants have been engineered too to overproduce recombinant proteins and chelating molecules such as citrate, phytochelatins, metallothioneins, phytosiderophores playing roles in chelation and assimilation of metal.

3.2 Phytoremediation of organic pollutants

Due to increased human activities including urbanization and industrialization, the pollution of organic pollutants in urban areas has been increased over the last decade. Urban and peri-urban soils are often polluted as consequence of human activities. The main sources of the urban organic pollutants are (1) the utilization of the pesticides in the urban environment, (2) the atmospheric deposition of organic pollutants in form gaseous and particulate by transport, (3) the using of urban waste composts as amendments in urban agriculture and (4) the development of urban industry. According to the results of bibliographic research over the last 20 years on website Web of Sciences, phytoremediation of organic pollutants in non-urban and urban soils generally involved several classes of compounds which are mostly polycyclic aromatic hydrocarbons (PAHs) [24, 25], polychlorinated biphenyls (PCBs) [26] and petroleum hydrocarbons (PHCs) [27] and others low molecular weight compounds such as benzene, toluene and xylene [2] (**Table 1**).

Phytoremediation for organic contaminants takes place at two levels: inside and outside of plant cells. Like the mechanisms of phytoextraction (absorption) which is the primary of phytoremediation for inorganic pollutants as described above (see Section 2.1), some low molecular weight organic contaminants can be taken up by root and then to be accumulated and/or degraded *in planta* [28]. However, most of organic contaminants are generally too large and/or hydrophobic therefore they cannot to be absorbed by plants. Two primary *ex planta* mechanisms of phytoremediation for organic contaminants are (1) rhizodegradation *via* the active microbial communities in the rhizosphere, and (2) phytodegradation *via* the plant enzymes. For rhizodegradation, rhizosphere microbial community through by their metabolic process transform the organic pollutants (hydrocarbon) to microbial biomass, bioenergy, carbon dioxide and also water for their development [2, 29]. For phytodegradation, plants used for phytoremediation excrete various extracellular enzymes including laccases, dehalogenases, nitrilase, nitroreductases and peroxidases degrading the organic contaminants [30]. Recently, numerous works have reported that different plant species and varieties are able to be used for phytoremediation of organic contaminants. Most of plant used belong to ornamental woody and herbaceous species [31]. Particularly, the utilization of different plant species of Asteraceae family, potential and suitable candidates, for phytoremediation of organic in urban areas was well quoted in the review presented by [32].

Over recent years, the number of works in phytoremediation for organic contaminants has intensely increased with many encouraging results that have emerged regarding the capacities of several plants to degrade specific organic contaminants. To make phytoremediation for organic compounds successful, it is fundamental to understand (1) the type of soil to be treated, (2) the concentration and the fate of each organic pollutants and (3) the relations between the physical, chemical and biological parameters. Urban soils are known to have particular characteristics that have mentioned above, therefore the application of this technology in urban polluted soils remains a daunting challenge for scientists. An exploratory bibliographic research on the Web of Science from 2000 to 2020 show that a few works use greenery to eliminate the organic pollutants in urban context since its application can be limited by many factors including climate and anthropogenic modifications of the soil (e.g. impacts on soils by urban-rural temperature contrast also known as urban heat islands) [33].

3.3 Challenges and perspectives of phytoremediation's application in urban soils

The urban context is very particular with regard to its location, spatial heterogeneity, pollution and usage. Even if urban soils are not intended to be reclaimed, there is still a risk to the health of the local population. It is for this reason that it is necessary to rehabilitate these soils. Many studies present the evidence results in utilization of different ornamental plant species for phytoremediation (e.g. family Asteraceae) can survive under such adverse urban conditions. In situations where the city budgets are limited and no alternative treatment can be carried out, the use of phytoremediated-plants could be affordable, sufficient, economically and community acceptable. Thus, plants play also a significant role in preservation of green spaces through enforcement of environmentally sustainable city planning. This application presents wealth of opportunities for city designers of urban landscapes and a good compromise to enhance urban diversity using phytoremediation in association with water infrastructures and open space on multiple scales.

Phytoremediation seems to be a promising technique but there are still many challenges, especially in an urban context. Indeed, the use of this technique is long (several decades) and restricted. Phytoremediation is thus limited by the area explored by plant roots and the low growth and low biomass produced. Moreover, this biomass cannot be used as compost because it is considered as contaminated waste. It is therefore necessary to select the right plant, adapted to urban soils, non-invasive in order not to alter the floristic diversity and capable of mobilizing metals even if they are not bioavailable. Thus, for each urban soil, a risk assessment should be carried out to protect local biodiversity before introducing alien species, but also a study should be carried out to better understand the interaction between the factors in the rhizosphere (metals/soil/microorganisms/plant roots).

Urban soils are increasingly being used for urban agriculture, either for private use or for small-scale local production. Thus, one of the big challenges is to cultivate while respecting food security and human health but there is a lack of data. To remediate to its problem, more and more works were focused on the combination of phytoremediation and food production [34]. At present, there are no large-scale studies, and most of this work reports on experiments with crop/phytoremediating plants combinations. There is always the problem of the biomass produced, can it be consumed? Can it be used as compost? Legislation in all countries is very vague or non-existent and needs to be strengthened. Research needs to be further continued to overcome these challenges of establishing food production on urban soils by carrying out studies on the translocation of pollutants in plants and their bioaccumulations, eco-toxicological risk assessment and soil legislation.

4. Improving the efficiency of phytoremediation in urban context

In spite of the fact that phytoremediation has a great of advantages in comparison to other technologies, it has also some limitations. The process of the phytoremediation is very slow from a few months to several years. The most of the plant used for phytoremediation have often small aboveground biomass and slow growth rate, and shallow root system, therefore very limits for their application in large-scale operations. Also, the low concentration of contaminants in form bioavailability in soils cause a low ability of contaminant absorption by plants.

To improve these limitations, one alternative that we will mention in this chapter is the use of (1) specific microorganisms such as fungi and bacteria, (2) earthworms, considered as 'ecosystem engineers' of soil, and (3) amendment such as biochar. All these complementary methods will permit to increase the growth of plants, biotic and abiotic stress tolerance and all the processes associated, such as mineral nutrient absorption, roots exudation and rhizosphere microbial activities, will be improve the process of the phytoremediation.

4.1 Using microorganisms (symbiont: fungi and bacteria)

4.1.1 Using fungi-assisted phytoremediation

A fungus (plural: fungi) belongs to the group of eukaryotic organisms. These organisms forms a kingdom that is separate from the other eukaryotic life kingdoms of plants and animals. Fungi are heterotroph, since they obtain carbon and energy from organic matter. Two major functional categories of fungi are saprophytic and mycorrhizal fungi. Saprophytic fungi decompose nonliving organic matter and they are important agents in soil mineralization processes and carbon cycle. Mycorrhiza are symbiotic species associated with vascular plants. There are eight main types of mycorrhizal symbioses based on their morphology and not on a biological reality [35].

According to pollutant type (organic and inorganic), the mycorrhizal fungi will be different. Whatever the pollutants, the selection of an appropriate host plant with mycorrhizae is of primary importance to improve phytoremediation. For organic pollutants such as polycyclic aromatic hydrocarbons (PAH), endophytic fungi is preferentially used to increase the efficiency of phytoremediation [36, 37]. For example, arbuscular myccorhizal fungi (AMF), belonging to the phylum *Glomeromycota,* form ubiquitous mutualistic interactions with roots of 80–90% of vascular plants species. AMF is widely used to degrade PAH. The hydrocarbons remediating potential of other endophytic fungi have been reported since the last decades. Thus, *Pestaliotopsis microspora* associated to the *Dendrobium* plant species have shown an efficient degradation potential of plastic polyester polyurethane. *Phomopsis liquidambari* degrade efficiently PAH in *Bischofia polycarpa* [36]. These symbiosis between endophytic fungi and vascular plants permit an increase of plant growth and hydrocarbons biodegradation by roots and its microflora associated, an improvement of adsorption and bioaccumulation of hydrocarbons by roots [38, 39].

For inorganic pollutants such as trace metals or metalloïds, some endophytic fungi, especially AMF that can increase the uptake of arsenic or other metals such as zinc, copper or lead [39]. Nevertheless, it has been shown that the most effective fungi in terms of host plant adaptation are ectomycorrhizae and ericoid mycorrhizae [35, 40, 41]. Indeed, the great development of the extraracinar mycelium allows it to explore a large volume of soil but also to store more metals and transform them into a less toxic form thanks to a wide range of enzymatic activities.

The interaction mycorrhizae-plant symbiosis and inorganic pollutants has three advantages. First, fungi can tolerate a high level of metal toxicity. Second, they are able to remove inorganic pollutants from soil and water. Finally, they promote plant growth even in polluted soils.

4.1.2 Using bacteria-assisted phytoremediation

In healthy soil, bacteria represents billons of unicellular organism and thousands of different species. Bacteria play a crucial role in ecosystem service of soil such as decomposers. As a consequent, bacteria release nutrients that other organisms could not access. Nevertheless, environmental and structural characteristics of urban soil greatly influence soil microbes. Indeed, anthropogenic impacts such as organic and inorganic pollutants in technosols and in urban runoff can shift the abundance and diversity of bacterial communities [42]. For example, it has been shown that in urban soils the main phyla identified are Acidobacteria, Actinobacteria and Proteobacteria.

In the rhizosphere zones, bacteria interact with plant root in form of commensalism or mutualism. These root associated beneficial bacteria that plays an important role in acquisition for nutrient, tolerance to abiotic stress and also defense against pests are referred to as the plant-growth-promoting rhizobacteria (PGPR) [43]. Therefore, PGPR have been mainly considered to use in phytoremediation in order to increase the efficiency of the phytoremediation. Recently, another bacterial type called plant growth-promoting endophytic bacteria (PGPE) which have been shown to act as PGPR are widely used in phytoremediation [44].

In the phytoremediation context, the microbial mechanisms direct and indirect that can improve the efficiency of phytoremediation are differ depending the pollutant types including organic or inorganic. Generally, root assisted-bacteria are used in order to improve the adaptation of hyperaccumulator plants to suboptimal urban soil conditions (see Section 2.1, 2.2 and 2.3) and ameliorate the efficiency of phytoremediation. For inorganic pollutants including trace metals, the mechanisms employed for enhance the phytoremediation involve improvement of plant growth by increasing mineral contents, plant metal tolerance by phytohormones products, and capacity of absorption and accumulation by producing organic acid and metal-specific ligands (e.g. siderophores) [45]. We can here cite some research works on the phytoremediation of metals facilitated by soil bacteria. The bacterial species *Bacillus* sp. MN3-4 which is a lead-resistant bacterium enhanced phytoremediation potential of plant *Alnus firma* by reducing the phytotoxic effects of metals [46]. A nickel-resistant PGPB *Pseudomonas* sp. A3R3 increased the capacity of Ni-accumulation of *Alyssum serpyllifolium* plant by production of ACC deaminase and IAA, siderophore synthesis and polymer hydrolyzing enzyme [47]. Besides, many works show that the use of plant growth-promoting rhizobacteria (PGPRs) as complementary process for metal phytoremediation leads to (i) higher plant growth by improving soil properties and biological activities under toxic metal stress, (ii) decrease phytotoxicity, and (iii) decrease oxidative damage to plant tissues that are exposed to high metal trace content by increasing antioxidant enzymatic systems [48, 49].

Unlike inorganic pollutants, for organic pollutants whose molecules contain principally carbon, the principal bacterial mechanisms when phytoremediation's applied is related to pollutant co-metabolism and/or degradation pathways [50]. In fact, exogenous as well as endogenous bacteria have a system of co-metabolism of the organic pollutants as the sole carbon source with amino acid, lipid, fatty acids and organic acids. Alternatively, these bacteria come to colonize in the rhizosphere and benefit the production of root exudates, consisting of sugar, fatty-acid, organic acids, amino acids and other carbon-containing compounds for growth and degrade these organic pollutants [51].

Although a lot of research points out many advantages this alternative technology, to our knowledge, no work on phytoremediation of pollutants facilitated by soil bacteria in urban areas has been carried out. To apply this technique in urban context, we must take into account all the parameters, consisting of bacterium, plant species, soil composition and nutrient (see Section 2), pollutant type and concentration as well as the competition with other organisms that can limit the use of phytoremediation in the field.

4.2 Using soil fauna: in case of earthworms

Earthworms act as soil ecosystem engineers because of their crucial role in building galleries and in the decomposition of organic matter; therefore they play an important role in agriculture production [52, 53]. In polluted soils, various species of earthworms including *Eisenia fetida*, *Lumbricus terrestris*, *Lumbricus rubellus* and *Aporrectodea caliginosa* can survive in soils polluted with metals and even accumulate heavy metals including Cd, Pb, Cu and Zn [54]. This leads to the ideas of earthworm's application for phytoremediation. On the one hand, earthworms can improve the soil physical and chemical properties and increase the soil fertility through an amelioration of the microbial activities. On the other hand, through their activity, earthworms increase the bioavailability of heavy metals in soils which is a primordial factor controlling the success of heavy metal phytoextraction [54–56]. In the case of mercury, for example, mercury changed from the stable crystalline iron oxide state to the mobile amorphous oxide state by earthworm's activities [57]. In spite of their important role in the bioavailability of heavy metals allowing the improvement of phytoremediation, the majority of studies using earthworms for phytoremediation has been developed to improve the capacity of microorganisms inoculated in soils (call bioaugmentation) to establish, survive and colonize the rhizosphere. Earthworms are known to help (1) settlement of inoculated microorganism, (2) enhancement of microbial survival (e.g. by supplying nutrients) and (3) distribution of microorganisms in soil, earthworms insuring transport.

A summary of the mechanisms direct and indirect of earthworm's effect on soil microorganisms and plants was presented in **Figure 2**.

Despite a large body of literature on the benefit for soil and plants by earthworm actions, the research on earthworms-assisted phytoremediation has just started on a laboratory scale with some encouraging results [55, 56]. The attention of this research topic is expanding by the time with an increasing the sum of times cited per year according to the citation report from Web of Science Core Collection between 2010 and 2020 (**Figure 3**). Outdoor experiments up to fields scale need to be investigated and documented.

4.3 Using soil amendment (biochar)

Urban soils are often nutrient poor and polluted. They are degrading more and more quickly with the loss of organic matter and soil permeability that cause the negative impacts on soil structure with increasing in soil density due to soil compaction and other factors. To overcome these deficiencies, the addition of natural organic matter including compost has been recognized to increase the bio-physico-chemical qualities of these urban soils [58–60]. Among the different composts, the application of biochar, which is a carbonaceous solid material, is used preferentially for urban soils. Biochar is derived from the pyrolysis of biomass. All cellulose, lignin and other non-carbonic materials gasify and are burned. Only pure carbon remains with approximately 40% of the carbon originally contained in biomass.

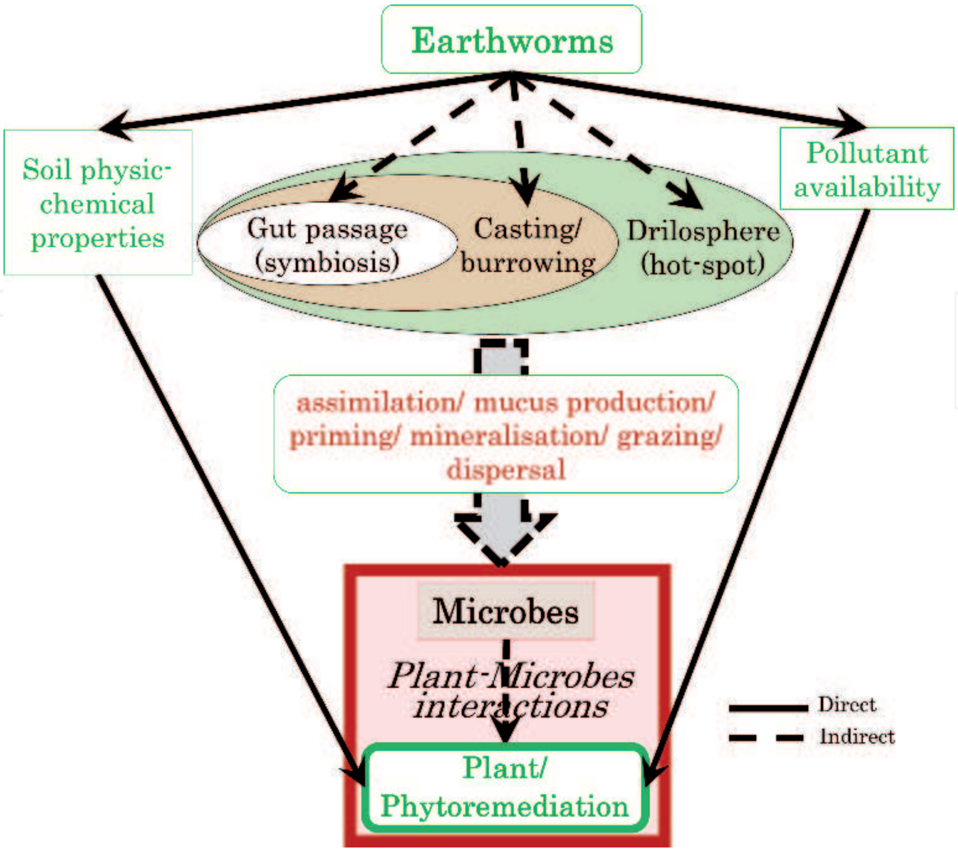

Figure 2.
Mechanisms direct and indirect of earthworm's effect on plant and microorganisms in the phytoremediation context.

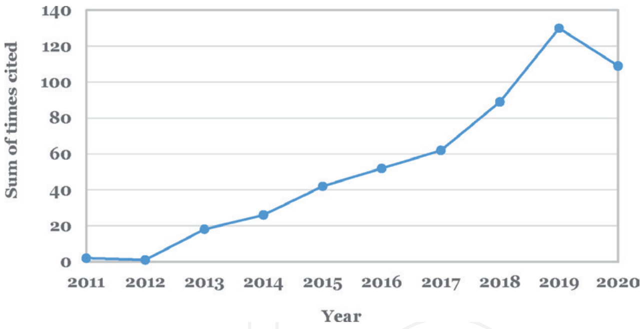

Figure 3.
Citation report of the sum of times cited per year on the topic "earthworms" and "phytoremediation" from web of sciences. This report reflects citations to source items indexes within web of science Core collection. Perform a cited reference search to include citations to items not indexed within web of science core collection.

Rather than an amendment (because it is very poor in nutrients), biochar would behave as a soil structure and perhaps as a catalyst, via mechanisms of action that are still poorly understood. The incorporation of biochar decreases the mobility and bioavailability of metals, thus decreasing their translocation in plants while improving the soil characteristics such as infiltration rate, hydraulic conductivity, porosity and therefore the water content. The growing of plants and water cycle is also improved.

Biochar, as a carbon-rich, stable and sustainable product, also acts as a carbon sink, which explains why it is attracting growing interest in the context of concerns about human-induced global warming. It could be one of the immediate solutions to the overall negative impact of urban and agricultural activities with the use of fossil carbon in the form of fuels, greenhouse gas emissions and tillage that degrades the carbon sink that humus constitutes.

Nevertheless, the application of biochar presents possible negative effects. Biochar may contain toxic elements naturally present in its composition and which may lead to an increase in pollution when incorporated. This can affect living organisms and the functioning of the soil. Moreover, because of the dust formed during their application, it present a risk for human health. There is still little data on its negative impacts.

To date, most of the studies has focused on the impact of compost on soil characteristics in agricultural area and relatively little data has been carried out in urban area. Future research should focus on the optimization of compost rates (quantity, depth…) in order to standardize the use of biochar on soil to minimize the bioaccessibility of pollutants and maximize soil/water relations and plants reestablishment [59].

5. Social aspects linked to phytoremediation in urban context

5.1 Perceptions and social acceptability of phytoremediation method: some elements for thought

The use of the words acceptability, social acceptance or social reception gives rise to terminological debates [61]. Acceptability is indeed a term vague enough to be used frequently [61]. We can nevertheless consider the social acceptability of a project as a process of social construction born from the confrontation of the arguments of the different actors and which results in an identification of the population concerned with the values carried by the said project. Some stress the fact that this dialog often comes down to the implementation of a communication strategy intended to convince the target audience as part of a top-down conception of a project [62]. The acceptance term is sometimes preferred but can imply a form of resignation of the inhabitants compared to a project conceived in a non-concerted way ([61], according to [63]). Some therefore prefer to use the term "acceptance" [61] after [64], others prefer the term "social reception". In fact, we can speak of acceptance of a project when it is appropriate by a population that identifies with the objectives pursued and the methods mobilized by it. This appropriation is conditioned by the perception of the project.

For psychology, perception is the function that allows the body to receive, process and interpret information received which comes from the surroundings through the senses. This construction is obviously specific to the type of information, to the individual or group who receives it and to the context in which it is disseminated. Thus a project will be perceived and therefore appropriate differently according to the economic, social, historical context, according to the modalities of diffusion of the information and the nature of this one, and obviously according to the type of actors diffusing and receiving the information and their expectations.

If we particularly consider phytoremediation projects, the perception by the population concerned is influenced by multiple factors: first of all, the identification of the risk associated with soil pollution and the potential benefits expected from phytoremediation [65]. This identification is closely linked to knowledge of the health risks involved. It was highlighted in a Quebec mining site, that the knowledge by all of a strong soil pollution whose effects on the health of populations are clearly highlighted, facilitates the acceptance of phytoremediation projects. In this case, the benefit is clearly identifiable and the populations are extremely favorable to a method of depollution considered as ecological.

However, if the populations of mining sites are alerted to the health risks linked to these forms of pollution [66] which is not necessarily the case in urban areas where pollution is old and associated with activities considered to be less polluting. Thus, the spreading of Parisian mud on the fields of farmers located in the immediate suburbs of Paris in the 19th century was not initially considered as a polluting activity [67]. In addition, the renewal of the population in a good number of urban regions leads to a lack of knowledge of the history of soils and associated pollution.

In most cases, the esthetic and landscaping criteria has an essential role in the reception that can be given to this type of project [68]. The revegetation of soils in neighborhoods that the image is devalued by an industrial or mining past and the presence of brownfields, constitutes a benefit clearly identifiable by the population who have been living there for a long time or more recently. Revegetation is often equated with an embellishment and an improvement of the living environment from an ecological point of view.

The different phytoremediation methods used, can, however, raise questions about the choice of species (sometimes non-native and poorly accepted by local residents), the fate of pollutants and the time required to obtain results [65]. Phytoextraction raises the question, for example, of the fate of plants that have absorbed a certain amount of pollutants, including trace metals, and their treatment [69].

Good reception of the project can be facilitated by working upstream with the inhabitants in order to make them aware of the characteristics of the different phytoremediation methods and their effects. Consultation on the landscapes desired by local residents would make it possible to consider the choice of species that can be used appreciated [61]. This work obviously requires a time of information and consultation that is added to the time necessary to obtain the first effects of the different phytoremediation methods.

It is also difficult to envisage social acceptability without considering the potential economic benefits. In terms of costs, phytoremediation is a much less expensive technique than conventional techniques, however it still seems to be little applied [70]. In this regard, it should be emphasized that local communities such as companies specializing in soil remediation are often ill-informed and poorly trained or little trained in this type of alternative techniques and prefer to apply better known and better controlled methods such as excavation and backfilling of polluted areas. It seems that phytoremediation is struggling to get out of the purely scientific and experimental sphere. The time required to obtain significant results is a constraint both for development companies, local authorities and for the population. In the process of acceptability of phytotechnologies, an articulation between these different temporalities constitutes an issue to be taken up.

In addition, the techniques of economic valuation of the biomass resulting from phytoremediation by the production of energy are still often experimental and little diffused and/or applied. Its transformation into energy, whether by thermodynamic processes (combustion, pyrolyse, roasting) or by biological processes (methanization), poses the problem of becoming pollutants and in particular of the trace metals contained in the biomass, in particular in the case phyto-extraction (ash after combustion, digestate after production of biogas). The acceptability of soil remediation projects through phytoremediation depends on the benefits known to society (population and decision-makers) and the value attributed to them.

5.2 Potential social benefits of phytoremediation

The social benefits attributed to phytoremediation can therefore be considered through the prism of ecosystem services. This concept, first imagined by ecologists, has been mobilized and widely publicized since the Millennium Ecosystem Assessment (2015); the objective sought was to promote the protection of ecosystems by assigning economic and social value to the services provided by them [71]. Ecosystem services can therefore be defined as the benefits provided by ecosystems to human societies. A general distinction is made between production (or supply) services, regulation services and cultural services. Despite the reservations which are made by ecologists and sociologists among others with regard to this concept and the reflections as to a "commodification of nature", this can be useful here to consider the potential economic and social benefits of phytoremediation operations [71, 72]. These are a few lines of inquiry and not an exhaustive analysis. The purpose of phytoremediation is to reconstitute an ecosystem allowing depollution of the soil or stabilization of pollutants in the soil.

The most directly perceptible benefit for the population is undoubtedly landscaped and esthetic. The revegetation of polluted sites, often fallow land can on the one hand radically modify the urban landscape and the image of districts or cities sometimes stigmatized by their industrial or mining past, and thus procure an embellishment to which the local populations are sensitive [61]. On the other hand, this revegetation can in certain conditions and ultimately provide spaces for relaxation and leisure. In this sense, these are the benefits associated with cultural services that can be highlighted.

The benefit most directly sought by this type of project is obviously soil remediation. It can be clearly identified by the population, particularly in regions where health risks are known. Beyond the management of this pollution, it is also the structure and fertility of the soils that will be improved if not restored: the greater permeability of these soils is an asset to limit runoff and potential flooding in certain cases and a restoration of the water cycle more generally, including filtering and purification functions provided by vegetation [13].

We should add that in the context of sustainable city projects, revegetation via phytoremediation can contribute to the objectives of reducing greenhouse gases and improving air quality, plants storing carbon in their tissues via photosynthesis. The plants introduced into phytoremediation operations, whether local or not, participate in the maintenance or dissemination of a certain diversity of flora and therefore fauna and can be integrated into larger projects for the maintenance or development of urban biodiversity. The areas benefiting from these projects can thus be associated with the construction of ecological corridors within the framework of the green and blue frames promoted in recent years at different territorial scales. Phytoremediation can therefore help to provide regulatory services for the restoration of these ecosystems in urban areas.

The valorization of the biomass produced within the framework of these revegetation operations, can in certain cases and in the long term, be envisaged of different forms. Burning and pyrolizing wood products produces gas. Oil from pyrolysis can also be used in the composition of certain fuels, while ash and biochar (vegetable charcoal) can be reincorporated into the soil as fertilizers. The roasting of this woody biomass provides fuel. Non-woody plant waste subjected to anaerobic digestion allows for the production not only of gas but also of digestates; these can also be reintroduced into the soil [13]. These are therefore production or supply services which can be highlighted and fairly easily economically quantifiable.

The assessment of these social and environmental amenities provided by phytoremediation projects are, however, for the most part complex to assess and account for economically, in particular regulation and cultural services. The monetary calculation of the direct or indirect services rendered could however minimize the real costs of soil rehabilitation projects and facilitate their wider implementation.

5.3 Potential eco-garden with plant used in phytoremediation

Phytoremediation is a plant-based technology that make us think about the potential eco-garden whom urban residents can profit the green and beautiful landscapes and easily accept it. Ecological gardens can be viewed in two ways depending on the target audience. For city managers, these gardens are installed in a sustainable way to cover polluted soils and thus limit the risks to the population. The plants that will be used are, in general, ornamental plants that will require little maintenance and will be durable over time. A list of ornamental plant species provided (see more in [31]) belonging to different plant groups: trees, shrub, and herbaceous which have a good potential phytoremediation for heavy metal are already used for remediate the polluted soils. For this purpose, the exploitation of ornamental plants could be an additional option. At the top, we raise the points that we need to take care when application of phytoremediation. We propose also that phytoremediation could be successfully exploited in urban territories; in these contexts, many herbaceous and others are suitable for planting because of their ornamental features and adaptability to inhabited areas.

For the surrounding population, these ecological gardens have several roles, first of all a food production role, an educational role by promoting social cohesion. Thus, one of the big challenges is to cultivate while respecting food security and human health. Research needs to be further continued to overcome these challenges of establishing food production in combination with phytoremediation in urban areas by carrying out studies on eco-toxicological risk assessment.

Phytoremediation consist of different process and mechanisms such as absorption and accumulation of pollutant in plant as well as degradation. In the case of the contaminants are absorbed and accumulated in plant, risks in allotments are higher because of transfer of pollutants to the food chain [73]. Phytoremediation with degradation process maybe more suitable. In all cases, it is recommended to take precautions when you want to install eco-gardens on the polluted soils with hyper accumulator plants. High precautions has to be paid to parks, playgrounds, kindergartens and urban zones where residents come into close contact with soils. There are various species of ornamental plants in the literature, the choice of plant species depends on the climate, the tastes and traditions of each country.

6. Conclusions

From what we can see, phytoremediation is indeed an ecological and economical technology, acceptable and efficient to remediate the polluted soils. However, this technology is not actually widely applied in the urban context but it has many advantages regardless of the technique chosen or the pollutants present. Thus, the redevelopment of urban land in cities has become a priority. Since the implementation in 2006 of the draft European Directive on soil protection, which gives priority to soil diagnosis and remediation, the general objective of the European strategy has been to protect soil and guarantee its sustainable use by preventing its degradation, preserving its functions and restoring degraded soils. Despite these many improvements, legislation on these soils is either non-existent or very vague. Moreover, we have very little experience with trials of remediation of urban soils by the technique of phytoremediation. Nevertheless, the first results are promising with a stabilization of pollution, a decrease in erosion, a decrease in heat islands, and an increase in biodiversity with the implementation of ecological corridors in urban soil management. Research needs to be further continued to overcome these gaps on urban soils.

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