Bioremediation of Lead Contaminated Soils for Sustainable Agriculture

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Abstract

Metal pollutants such as lead, zinc, and copper are among the most widespread pollutants in the environment and especially in our soils, their origin is diverse and their persistence is worrying. In Algeria, the main sources of pollution are petroleum derivatives and industrial effluent, and studies have found metal levels up to 2712 ppm for Pb (Lead), 910 ppm for Zn (Zinc), and 10.18 ppm for Cd (Cadmium). It has become essential to control this pollution and find sustainable solutions for soil remediation and conservation. Several studies are directed towards new solutions for soil decontamination, bioremediation, and other promising techniques which are economical and above all more respectful of the environment. One of these innovative techniques is phytoremediation, the use of the capacity of the vegetation to bio-remediate varying concentrations of heavy metals for the rehabilitation of contaminated soils. However, these so-called hyper-accumulating plants have relatively low biomass, slow growth, and different rates of accumulation depending on the species and the metallic element. Various reports reflected the positive influence of earthworms on plant biomass and their indispensable role as a soil engineer. The aim of this chapter is to study the possibility of using this macro-invertebrate (*Lumbricus sp.*) to increase the efficiency of phytoremediation processes of *Hordeum vulgare*.

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Keywords

Barley · Bioaccumulation · Earthworms · Lead · Phytoremediation · Soil pollution

Abbreviations

BCF	Bioconcentration factors
CCME	Canadian Council of Ministers of the Environment
Cd	Cadmium
CEC	Cation-exchange capacity
Co	Cobalt
Cr	Chromium
Cu	Copper
DOC	Dissolved organic carbon
DW	Dry weight
EDTA	Ethylene diamine tetraacetic acid
EW	Earthworm
Fe	Iron
Hg	Mercury
$mg{\cdot}g^{-1}$	Milligram per gram
Mo	Molybdenum
Ni	Nickel
OECD	Organization for Economic and Cooperation and Development
OM	Organic matter
Pb	Lead
pH	Potential hydrogen
ppm	Part per million = $\mu g.g^{-1}$ = $mg.kg^{-1}$
SD	Standard deviation
Se	Selenium
SOM	Soil organic matter
t/y	ton per year
UE	European Union
Zn	Zinc
$\mu g.g^{-1}$	micro gram per gram

10.1 Introduction

Anthropogenic activities are responsible for the contamination of soils with various components. Industrial activities, agriculture, and automobile traffic are the main sources of contamination by various pollutants (Almehdi et al. 2019; Azizollahi et al. 2019; Kumari and Dey 2019; Colandini 1997; Raj et al. 2020; Banerjee et al. 2020), among them heavy metals whose levels in the soil receive great attention due to their negative consequences on biota as Pb (lead) and Cd (cadmium) (Li et al. 2009; Cheng and Wong 2002; Li NY et al. 2009).

Lead tends to have maximum toxic effect; its concentrations in lithosphere are aggravated by anthropogenic activity (Baize 1997). Lead is harmful to living entity at trace amounts and can also be toxic (Uzu et al. 2009). Pb in soil environment destroys the ecosystem homeostasis, inhibits plant growth leading to environmental degradation and human prosperity (Mishra et al. 2006; Zeng et al. 2006).

In Algeria, petroleum derivatives and industries are the population sources. There are relatively few data on soil pollution by heavy metals; no inventory on metal polluted soils has been done so far. However, there are some studies on metallic pollutants in the soil of various sources (road traffic and industrial effluent, etc.), for example, in the region of Tiaret—Algeria most of the soils which are near roads are contaminated by heavy metals and specifically by lead with concentration ranging from 20 $mg.g^{-1}$ to 4780 $mg.g^{-1}$.

Soil is the principal natural resource of humanity (Singh et al. 2020); its remediation has become necessary to conserve soils and water resources, the use of biological treatment (plants, bacteria, and invertebrates) to decontaminate soils is very promising (Jhariya et al. 2019a, b). However, bioremediation processes are still limited. The use of earthworms in bioremediation processes can increase its effectiveness (Eslami et al. 2019; Meena et al. 2018).

The introduction of the macro-invertebrates such as earthworms into soil contaminated with metals has been suggested to improve the phytoremediation capacity of vegetation (Lemtiri et al. 2016; Jusselme et al. 2012). Several experiments have been carried out using the association (plant–earthworms) for soil decontamination; earthworm activities enhance the metal availability as well as regulate soil structure and quality.

Earthworms are identified as ecosystem engineers for their functional role on long time span on properties of soil (physical, chemical, and biological) (Edwards and Bohlen 1996; Blouin et al. 2013; Bityutskii et al. 2016; Singh et al. 2016). They can be extremely affected by soil pollution and accumulated contaminants in their bodies. These characteristics, among others, have allowed their use as indicators of the contamination of the soil (Lanno et al. 2004; Xiao et al. 2006; Meena and Lal 2018). Edwards and Bohlen (1992) underline the interest of using earthworms in the biomonitoring of soil quality (De Vaufleury et al. 2013). It can be an advantage in soil remediation (Singh et al. 2020).

This chapter deals with the role of earthworms on lead phytoremediation and soil sustainability.

10.2 Soil Contamination by Lead: A Worldwide Problem

Natural presence of metals is very common. Certain elements (zinc and copper) are required for the biota in low doses. Human activities are the source of soil contamination by various organic and inorganic components. Heavy metals produced by industrial activities, agriculture, and road traffic have reached high levels in the soil,

Table 10.1 Standards for maximum levels in soils of some toxic metals (mg.kg^{-1} DW) enacted by the EU and various OECD countries (Ramade 2011)

Country	Metal	Maximum levels in soils
EU	Cd	3
	Cr	200
	Cu	140
	Pb	300
	Zn	300
Canada	Cd	3
	Cr	70
	Cu	150
	Pb	375
	Zn	600
France	Cd	2
	Cr	150
	Cu	100
	Pb	100
	Zn	300
GB	Cd	3
	Cr	400
	Cu	135
	Pb	300
	Zn	300
Holland	Cd	0.8
	Cr	100
	Cu	36
	Pb	85
	Zn	140
Sweden	Cd	0.4
	Cr	30
	Cu	40
	Pb	40
	Zn	75
Swiss	Cd	0.8
	Cr	75
	Cu	50
	Pb	50
	Zn	200

even toxic for some, in many regions (Ha et al. 2011; Jiang et al. 2012; Adriano 2001; Alkorta et al. 2004) and it has become more severe than other soil pollution (Demarco et al. 2019; Gómez-Garrido et al. 2018; Guo et al. 2019; Jeelani et al. 2018; Liu et al. 2018).

The contamination occurs when the concentration of an element in the environment increases beyond the values usually encountered (Table 10.1) (Alloway 1997).

Table 10.2 Global lead emission to land from all sources (Nriagu and Pacyna 1988 cited in Thornton 1995)

Sources	Emissions to land (t/y)
Metals and mining industry	329,100–791,000
Use and elimination of Pb	215,800–461,700
Other sources	57,190–303,700
Atmospheric fallout	202,000–263,000
Total	804,090–1,819,400

The toxicity of metals depends on their content in the medium and their chemical form, adding to this the physicochemical and mineralogical characteristics of the environment which influences the mobility and bioavailability of these elements and their accumulation by living beings (bacteria, plants, animals, and humans) (Baize 1997; Ebadi and Hisoriev 2017; Galal et al. 2019; Nan et al. 2019; Mai et al. 2019). Among the metallic elements mentioned, lead is toxic from the trace stage; it is probably the most known pollutant in public opinion. Its accumulation and transfer constitute a risk for public health, animals, and plants, but also for the natural environment as a whole. The estimation of heavy metal contents in soils is a crucial step in order to assess the risks and better remedy them (Blum et al. 1997; Meena et al. 2020a, b).

Lead is naturally present in the earth’s crust, its average abundance is estimated at around 15 ppm (Kabata-Pendias and Pendias 2001), generally in poorly soluble form. Inorganic derivatives are present in waters, sediments, soils, atmosphere and possibly in micro-traces in living organisms. Uncontaminated soils would contain 10 to 30 mg.kg^{-1} (Nriagu 1978; Baize 2002). Various forms of Pb are found in soil particles (Raskin and Ensley 2000).

Accumulation of Pb into the soil occurs mainly in the surface horizons (Sterckeman et al. 2000; Huynh 2009) and more precisely in horizons rich in OM (organic matter). The Pb contents then decrease more deeply (De Abreu et al. 1998; Huynh 2009). This is explained by the fact that the Pb is not very mobile. Being mainly associated with clays, oxides, iron hydroxides, and OM, it is only mobile when it forms soluble organic complexes and/or the soil has exceeded its absorption capacity for Pb (Morlot 1996; Raskin and Ensley 2000).

According to Ramade (1993), anthropogenic contributions of Pb are ten times greater than natural contributions (volcanism, erosion, wildfires, etc.), 99.7% of atmospheric Pb emissions are of anthropogenic origin, and a large part related to automobile traffic (Colandini 1997). The level of Pb in the soil surface has reached values of around 2% of DW (dry weight) in the soil at several sites in the world (Kabata-Pendias and Pendias 2001). Pb levels in soil are from various sources (Table 10.2). In Algerian soils several studies have shown the extent of this pollution and road traffic seems to be the main source of metallic pollution of the soils (Table 10.3).

Table 10.3 Heavy metals concentration in Algerian soils (ppm)

Origin of the pollution	Pollutant	Mean	Range	Author
Road traffic	Pb	1714,4	845,6–2712	Maatoug et al. (2013)
	Zn	666,5	179–910	Zerrouki (2014)
	Cu	3,18	0,8–13	
	Pb	643,61	–	Bouras et al. (2010)
	Zn	836,93	–	
Atmospheric fallout in the ground (industrial zone)	Pb	3,42	0–13.7	Benahmed et al. (2016)
	Zn	7,45	0–21.96	
Industrial effluent	Pb	–	7.99–39.14	Kebir and Bouhadjera (2011)
	Zn	–	21.15–731.08	
	Cu	–	4.32–15.32	
	Cd	–	1.89–10.18	

The evaluation of lead concentrations in soil, which may be harmful or even toxic to plants, is difficult; several authors have estimated these concentrations between 100 and 500 ppm (Kabata-Pendias and Pendias 2001). Pb disrupts the physiological mechanisms of plants and affects their growth and morphogenesis. It inhibits germination, causes the formation of small plants, and affects the morphology of the roots. Inhibition of the division of cells and their elongation are the most often reported phenomenon to explain its effects on the roots (Kopittke et al. 2007; Patra et al. 2004; Seregin and Ivanov 2001; Makowski et al. 2002).

Lead concentrations toxic to plants vary according to the studies; it strongly depends on the species of plant studied, but also on the culture method and environmental factors. Rooney et al. (1999) showed that for concentrations of metals extractable with EDTA in a soil reaching 800 mg.kg^{-1}, the growth of Raygrass was not affected. Päivöke (2002), on the other hand, showed that the toxicity of Pb to peas is dependent upon plant age and Pb concentration in the soil. However, he reports harmful effects on plant growth for lead concentrations below 500 mg.kg^{-1}. Liu et al. (2003) demonstrated that the sensitivity or tolerance of plants to lead was cultivar-dependent; the toxicity strongly depends on the behavior of plants towards this metal.

10.3 Earthworms for Improving Phytoremediation Process

Although phytoremediation has several advantages, natural process often carried out on-site and less costly than other technologies (Jhariya et al. 2018a, b). The majority of hyper-accumulative plants used for phytoremediation have a low biomass production and a slow growth rate, and in some cases trace elements have a harmful effect on them (phytotoxicity, inhibition of growth and metabolism, etc.); these negative effects depend on the element and its level in the soil (Salt et al. 1998; Shah and Nongkynrih 2007; Singh et al. 2003).

Table 10.4 Abundance and biomass of soil fauna in temperate regions (Gobat et al. 2010)

Group	Individuals/m^2	Biomass (g/m^2)
Protozoa	10^7–10^{11}	6 à ⍰30
Nematodes	1 à 30 millions	1–30
Acari	20,000–400,000	0.2–0.4
Collembola	20,000–400,000	0.2–0.4
Myriapods		
Diplopods	20–700	0.5–12.5
Chilopods	100–400	1–10
Isopods	Up to 1800	Up to 4
Insect larvae	Up to 500	4.5
Earthworms	50–400	20–400

However, a plant applied for metal phytoremediation should be able to accumulate high concentrations but also reflect higher growth and development (Lemtiri et al. 2016; Banerjee et al. 2018). To overcome these drawbacks earthworms have been found to increase the phytoextraction of pollutants (Lemtiri et al. 2016; Jusselme et al. 2012, 2015; Huynh 2009).

Earthworms can increase plant biomass, in some cases tend to adjust in soils with high level of mental concentration and increase the availability of pollutants; their activities must be considered in phytoremediation strategies (Jana 2009; Azhar-u-ddin et al. 2020). In fact, earthworms positively affect plant biomass in 75% of cases (an increase in aboveground and root biomass is observed) (Brown et al. 1999; Jana 2009), and the growth of hyper-accumulating plants (Jusselme et al. 2015; Huynh 2009) and have a favorable impact on the soil and its organisms.

Earthworms are soil engineering organisms; they alter soil resource availability for organisms (Jones et al. 1994; Lavelle 1996). They tend to be important organisms in soil (Huynh 2009) and are known for their important biological functions (Table 10.4). Incorporation of OM in soils promotes proper biogeochemical cycling and maintenance of favorable physicochemical conditions for biota (Brown et al. 1999, 2000; Lavelle 1988; Lavelle et al. 1998, 2006; Blouin et al. 2013; Meena et al. 2020; Kumar et al. 2020). Ecological category of earthworms determines their functionality in soil environment (Bouche 1977).

However, it seems that all earthworms increase heavy metals availability in soil and influence their mobility (Sizmur and Hodson 2009). Significant differences in bioaccumulation have been reported between eco-physiologically distinct earthworm species (Morgan et al. 1986, 1993, 1999; Beyer et al. 1987; Morgan and Morgan 1992, 1999; Van Vliet et al. 2005; Kamitani and Kaneko 2007). The endogens and the anecics are the most influential among the various earthworm species (Bouche 1977).

Earthworms have an impact on the dynamics of metals (Wen et al. 2004; Devliegher and Verstraete 1997 in Huynh 2009). They raise the availability of metals due to the decomposition of OM (Wen et al. 2004). Further, it also affects their distribution in soils (Zorn et al. 2005). Thus, the presence of earthworm *Lumbricus terrestris* increases the availability of copper by 6% (Devliegher and Verstraete 1995 in Huynh 2009). However, Abdul Rida (1996) considers that the impact of earthworms reflects lesser bioaccumulation in plants under low pollution level.

The effect of heavy metals on earthworms varies according to species, their ability to adapt to pollution, stage of development, diet, and place of life (Depta et al. 1999). Earthworms tend to be most sensitive than invertebrates towards metals (Bengtsson et al. 1992).

Metal accumulation in earthworms varies as per its chemical nature and soil properties and is generally higher than in other animal species (Depta et al. 1999; Beyer et al. 1982).

Earthworms can act on the growth and metals uptake by plants, either directly by modifying the physicochemical parameters of the soil (pH and the DOC level) or indirectly by modifying the communities of microorganisms present in soils (Gaur and Adholeya 2004; Jusselme et al. 2015; Eisenhauer et al. 2009; Ortiz-Ceballos 2007; Sizmur and Hodson 2009; Ma et al. 2006a).

Several works report the earthworm impact on metal accumulation of plants (Table 10.5) as a part of phytoextraction process (Jana 2009). For example, the *Pheretima* (*Metaphire*) genus increases the bioavailability of zinc in artificially contaminated soils and increases the aboveground and root biomass as well as the zinc concentrations of two plants *Lolium multiflorum* and *Brassica sp.* (Wang et al. 2006). The same positive effect on biomass and accumulation is observed for *Metaphire gillelmi* earthworms and the plant ryegrass (*Lolium multiflorum*) in soils artificially contaminated with copper and enriched in OM by the addition of straw (Jana 2009).

The tropical species *Pontoscolex corethrurus* also improves the phytoextraction of Pb by the plant *Lantana camara* in soils artificially doped with 500 and 1000 μg. $g^{-1}$of Pb (Duarte et al. 2012; Huynh 2009), and that the soluble and exchangeable fraction of Pb significantly decreases under earthworm presence in natural soil contamination (Duarte et al. 2012).

Another study, in microcosms on the soil of an old mining site contaminated by several metals (Pb, Zn, Cd, and Cu) involving the earthworm *Eisenia fetida* and plants (*Zea mays*) and (*Hordeum vulgare*), reports an increased rate of accumulation of these elements in both plant species and in all of their organs (Jana 2009).

10.4 Phytoextraction of Lead by *Hordeum vulgare* Under Controlled Conditions

Barley, considered as a hyper-accumulator plant of heavy metals (Morel 1997). It accumulates trace elements to different degrees depending on the metal and its level in the soil. In an agricultural soil contaminated with lead, barley accumulates up to 2% of the Pb in soil (Maatoug et al. 2013).

Table 10.5 Various publications which have studied (directly or indirectly) the effects of earthworms on the phytoremediation of soils polluted by heavy metals

Earthworms	Plants	Heavy metals	Authors
Eisenia fetida	*Vicia faba,* *Zea mays*	Cu, Zn, Pb, Cd	Lemtiri et al. (2016)
	Brassica juncea L.	Cd	Kaur et al. (2018)
	Neyraudia reynaudiana	Pb, Zn	Li et al. (2018)
	Vetiver grass	Cd	Wu et al. (2020)
	Stachys inflata	Pb, Zn	Mahohi and Raiesi (2019)
	Zea mays, *Hordeum vulgare.*	Pb, Zn, Cd, Cu	Ruiz et al. (2009)
	Phaseolus vulgaris L.	Se	Azhar-u-ddin et al. (2020)
	Paulownia tomentosa, *Cytisus scoparius*	Pb, Cr, Cd, Zn, Cu, Ni	Macci et al. (2012)
Eisenia andrei	*Canavalia ensiformis*	Cu	Santana et al. (2019)
Pheretima guillelmi	*Leucaena leucocephala*	Pb, Zn	Ma et al. (2003)
Pheretima sp.	*Lolium multiflorum,* *Brassica juncea*	Zn	Wang et al. (2006)
	Lolium multiflorum, *Brassica juncea*	Cd	Yu et al. (2005)
Lumbricus terrestris	*Pennisetum purpureum*	Pb	Das and Osborne (2018)
	Zea mays *Hordeum vulgare*	Pb, Zn, Cu	Ruiz et al. (2011)
Lumbricus rubellus	*Zea mays L.*	Cd	Aghababaei et al. (2014)
Lumbricus sp.	*Hordeum vulgare*	Pb	Boukirat et al. (2017)
Pontoscolex corethrurus	*Lantana camara*	Pb	Jusselme et al. (2012)
	Acacia mangium	Pb, Ni, Cr	Bongoua-Devisme et al. (2019)
Metaphire guillelmi	*Lolium multiflorum*	Cu	Wang et al. (2007)

Pb unlike other elements (Zn, Cu, etc.) is not an essential element because although present in plants, it does not participate in any known physiological or biochemical function (Marschner 1995). It is absorbed by the plant according to a different uptake pathway than that of the essential elements (Lemtiri et al. 2016).

The accumulation of Pb by barley is influenced by several parameters related to the soil but also to the form in which the pollutant is found. Zerrouki (2014) reported that parameters such as pH, CEC, and clay content have a significant effect on the bioaccumulation of metals by barley. However, the interaction between the different metals and the forms in which they are present in the soil can modify their bioavailability for the plant.

Table 10.6 Descriptive statistics of lead concentrations (μg.g^{-1} DW) in soil–plant system

Attributes	*N*	Mean ± SD	Min	Max
Pb-soil	16	331.88 ± 66.95	200.00	430.00
Pb-barley	16	59.44 ± 13.16	38.00	75.00
Control-soil	4	50.00 ± 21.60	20.00	70.00
Control-barley	4	11.75 ± 3.10	9.00	16.00

We studied the bioaccumulation of barley under controlled conditions in artificially contaminated soils by lead 331.88 ± 66.95 μg.g^{-1}, the concentrations accumulated by barley were 59.44 ± 13.16 μg.g^{-1}, these concentrations greatly exceed those found in barley cultivated under the same conditions on an unpolluted soil 50.00 ± 21.60 μg.g^{-1} with a concentration in the order of 11.75 ± 3.10 μg.g^{-1}, (Table 10.6) (Boukirat et al. 2017).

The accumulation of lead by barley was the subject of a study in soils with a high polymetallic load (Pb, Cu, Zn). Maatoug et al. (2013) reported that for lead concentrations of 1714.39 ± 512.62 μg.g^{-1}, barley accumulates up to 36.28 ± 14.90 μg.g^{-1}. The removal of trace element by plants is related to the supply of soil (Nguyen 2007). The correlation between soil lead and lead accumulated by barley is positive and highly significant ($r = 0.688^{**}$, $p < 0.001$) (Boukirat et al. 2017). An increasing trend between metal levels in the soil and the concentration accumulated in plants was recorded after an artificial contamination of a healthy soil by saline solutions of metals (Mahler et al. 1978; Mitchell 1978). In general, the Pb concentrations of a plant are closely correlated to the Pb concentrations of the soil.

Barley accumulates 18.11% of lead from the soil under controlled conditions (Fig. 10.2), a high rate compared to that found by Maatoug et al. (2013) which is 2%. The form in which lead is added to the soil may explain the large amount accumulated. Diehl et al. (1983) found that Pb particles in soils are rapidly converted into water-soluble compounds, readily disposable to plants.

Soil physicochemical parameters influence metals mobility in the soil and their bioavailability but also their bioaccumulation by plants (Boukirat et al. 2017; Maatoug et al. 2013). The constituents of the soil, in particular clays and OM can interact with metals through different chemical interactions, all these interactions limit the bioavailability of these metals in the soil (Tanner and Headley 2011).

Soil pH regulates the absorption of Pb at variable concentrations in various species (Seiler and Paganelli 1987) and clays which are fine fractions which intervene mainly during the phenomena of retention and fixation of heavy metals (Sanders 1983).

Lead solubility and mobility in soil depend on the type of Pb compound that has been added to the soil. For example, Pb nitrates are very soluble and will be easily leached from the soil (CCME 1999) and easily bioaccumulated by the plant (Boukirat et al. 2017).

10.5 Bioaccumulation of Lead by Earthworms (*Lumbricus sp.*)

Earthworms are known for their bioaccumulation capacity (Hopkin 1989) and for their important role in soil remediation (Singh et al. 2020). They are constantly in contact with the soil, whether in their dermis or during ingestion of soil. Earthworms tend to accumulate pollutants of the soil environment. Differences in metal concentrations between eco-physiologically different species of earthworms are reported by Morgan et al. (1993). Also depending on their ecological class (endogeic, epigeic or anecic), earthworms are more or less sensitive to metallic trace elements (Tomlin 1992).

Earthworms that live in soils contaminated by metals, mainly from anthropogenic sources, accumulate high concentrations of heavy metals (Ireland 1983; Morgan and Morgan 1988; Dai et al. 2004). Metal bioaccumulation in their tissues relies on the species and the characteristics of their living environment, in particular the composition of the soil and its pH (Van Gestel and Ma 1988; Morgan and Morgan 1991, 1999). Morgan et al. (1993) emphasize the importance of earthworms determining biotic factors, which regulates metal accumulation. However, the study of the bioavailability of pollution in terrestrial environments by measuring the bioaccumulation of metals by earthworm species is quite difficult since the bioavailability data are specific to each species (De Vaufleury et al. 2013).

Nahmani et al. (2007) mentioned difficulty in establishing simple statistical relationships between the metals concentrations in organisms and those of abiotic components of the environment. Thereby, better understanding of the potential of different species of earthworms to bioaccumulate pollutants according to the nature of the metals and their concentration is primordial (De Vaufleury et al. 2013).

Earthworms that live in soils polluted by metals due to the proximity of motorways (Gish and Christensen 1973) or mining (Ireland 1975; Dai et al. 2004) or the spreading of waste (Helmke et al. 1979) have much higher levels of heavy metals than those which develop in unpolluted areas.

On soils artificially contaminated with lead 342.50 ± 54.59 $\mu g.g^{-1}$, the earthworms *Lumbricus sp.* accumulate approximately 24.01 ± 10.97 $\mu g.g^{-1}$ (Table 10.7). Higher accumulation compared to their concentrations 8.20 ± 0.48 $\mu g.g^{-1}$ in unpolluted soils whose concentration is $<100\ \mu g.g^{-1}$. The concentrations of lead in earthworm tissue are positively correlated with Pb-soil concentrations with a correlation coefficient ($r = 0.92^{**}$, $p < 0.000$) (Boukirat et al. 2017).

An increase in the concentrations of Pb in the earthworm *Eisenia fetida* exposed to the highest contamination (2000 $mg.kg^{-1}$) is observed, but this remains much lower than that of the environment (Scaps et al. 1997). These results agree with those of Grelle and Descamps (1998) and Boukirat et al. (2017).

The ability of earthworms to accumulate Pb makes them useful indicators of lead pollution of the soil. Usually the lead concentrations in the soil exceed that of earthworms. On the other hand, in certain situations, high concentrations of Pb combined with low calcium content in an acidic soil can induce a greater accumulation of lead coming from the soil in earthworms (Ireland 1979).

Table 10.7 Descriptive statistics of lead concentrations (μg.g^{-1} DW) in soil–earthworms system

Attributes	*N*	Mean ± SD	Min	Max
Pb-soil	16	342.50 ± 54.59	250.00	440.00
Pb-EW	16	24.01 ± 10.97	12.55	54.54
Control-soil	4	70.00 ± 16.33	50.00	90.00
Control-EW	4	8.20 ± 0.48	7.50	8.59

In *Aporrectodea tubulata* the Pb concentration varies from 5 mg.kg^{-1} to 12 mg.kg^{-1} in a pH range between 7.1 and 4.9 (Beyer et al. 1987).

The accumulation of Cd and Zn in the body of earthworms is variable; it depends on the species, the soil nature, duration of the experiments (De Vaufleury et al. 2013). The low bioavailability of metals (Pb, Zn, and Cu) from contaminated soil at alkaline pH has been confirmed in *Lumbricus terrestris* in soils that are not rich in nutrients with the absence of toxic effects (Kennette et al. 2002). The variation in soil pH also influences the accumulation of lead by earthworms *Lumbricus sp.* (Boukirat et al. 2017).

The nature of the soil is of primordial importance in the bioaccumulation and toxicity of metals in earthworms (Van Gestel 1992). Clays, due to their properties, play a very important role in the availability of heavy metals. Li and Li (2000) showed that clay minerals can adsorb metals and immobilize them. The metals can also form an organometallic complex by complexing with soil organic matter (SOM) (Lamy 2000). Heavy metals toxicity depends also on the nature of the clay and SOM. Lock and Janssen (2001) showed that for *Enchytraeus albidus*, the toxicity of Zn and Cd depends on the nature of the clay used (kaolinite, illite, and montmorillonite) and on OM (fallen leaves of various dead trees or stems of nettles or reeds).

The accumulation of metals occurs when the concentration factor in the soil is >1 (Van Hook 1974). The accumulation rates in earthworms vary depending on the heavy metal studied 16.0 for Cd, 4.1 for Zn, 1.1 for Cu, 0.5 for Ni, and 0.4 for Pb (Abdul Rida 1996; Van Hook 1974; Van Rhee 1977; Czarnowska and Jopkiewicz 1978; Kennette et al. 2002).

The level of lead accumulated by *Lumbricus sp.* is 7.24% of soil lead, 24.01 ± 10.97 μg.g^{1} DW, BCF: 0.07. Compared to the results found in other studies on the accumulation of heavy metals by earthworms low values are recorded. However, a monometallic pollution combined with specific behaviors for each species and between the different ecological categories can explain the low bioconcentration factor (BCF) (Boukirat 2018).

Morgan et al. (1999) report that earthworms (*Lumbricus rubellus*) survive in the soil of the metalliferous site of Rudry, South Wales (GB) are exposed to concentrations of Pb (2337 μg.g^{-1} DW), Zn (5902 μg.g^{-1} DW), and Cd (604 μg.g^{-1} DW). Their tissues contain substantial amounts of the three metals (Cd: 1212 μg.g^{-1} DW, BCF: 2.01; Zn: 2470 μg.g^{-1} DW, BCF: 0.42; and Pb: 892 μg.g^{-1}DW, BCF: 0.38) (De Vaufleury et al. 2013).

Several studies have shown properties of soil influence Pb absorption by *Eisenia andrei* (Smith et al. 2012; Peijnenburg et al. 1999; Spurgeon and Hopkin 1995; Bradham et al. 2006; Luo et al. 2014).

Higher Pb concentrations in earthworm tissue are associated with high clay and silt levels, and high lead concentrations in soil, combined with acidic pH (Boukirat 2018). Luo et al. (2014) reported the bioavailability of Pb and its toxicity on earthworms. He further reported that Pb concentrations in earthworm tissues reflect positive correlation with total soil Pb concentration and the available fraction, the content of sand and Fe. Negative correlation was found between earthworm accumulation with the content of clay, silt, and CEC. They also point out that the concentrations of Pb in earthworms are well predicted by the total concentrations of Pb and silt rate in the soils.

Numerous studies have made it possible to identify the parameters on which the bioaccumulation process depends: trace element and its concentration in the soil, the species and the ecological category of the earthworm, the physical and chemical properties of the soil (Ma 1982; Marino et al. 1992; Abdul Rida 1996; Ireland 1979; Ash and Lee 1980; Ireland and Richards 1981; Smith 1996; Jusselme et al. 2013; Boukirat et al. 2017). According to De Vaufleury et al. (2013) it is primordial to study the factors that control the mobilization and absorption of the compounds in other terrestrial animal species with more varied lifestyles and anatomical and physiological characteristics.

10.6 Impact of the Plant/Earthworm Association on Soil Bioremediation

The positive effect of earthworms on vegetation was confirmed by the study of Wollny (1890) on cereals and legumes. He observed an increase of 35–50% in grain yield and 40% for straw (Jana 2009), combined with their impact on soil fertility and the bioavailability of nutrients, their use as reinforcement for soil phytoremediation seems promising.

The interaction between plants and earthworms varies the concentrations of lead accumulated by each of them (Boukirat et al. 2017). For example, Lemtiri et al. (2016) found that adding earthworms to contaminated soil with Pb, Zn, and Cu does not affect the concentrations of metals in plants. On the other hand, Wen et al. (2004) and Azhar-u-ddin et al. (2020) reported an increase in the concentration of metals in plants in the presence of earthworms.

The influence of *Hordeum vulgare* and *Lumbricus sp.* association on lead bioaccumulation by each of them was studied in a greenhouse experiment with different arrangements: (1) with or without inoculation of earthworms; (2) with or without the presence of the plant (Boukirat et al. 2017) their interaction is represented in (Fig. 10.1). The concentrations of Pb accumulated by the association of barley and earthworms are 38.00 ± 5.68 $\mu g.g^{-1}$ and 26.01 ± 6.66 $\mu g.g^{-1}$, respectively, and for polluted soils it ranged from 500 $\mu g.g^{-1}$ to 2000 $\mu g.g^{-1}$, a

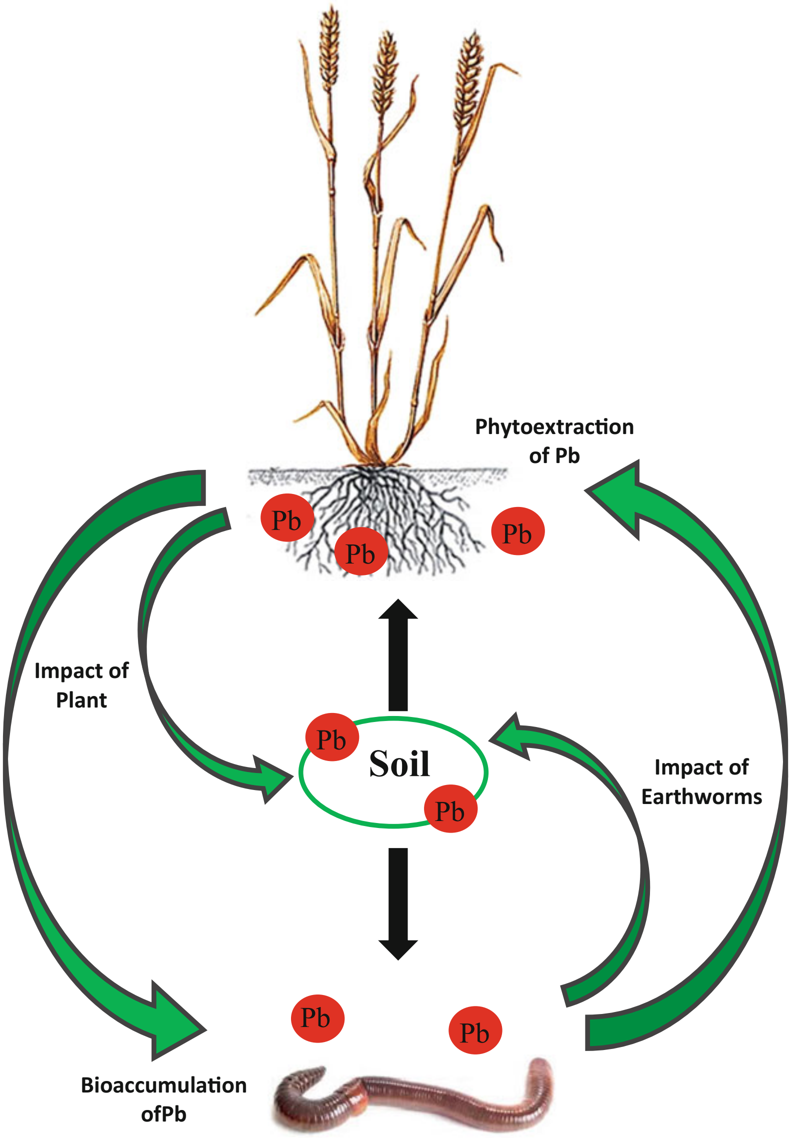

Fig. 10.1 Diagram representing soil, plant, and earthworms interactions under lead pollution

strong accumulation relative to the control soil (Pb <100 μg.g^{-1}) 20.25 ± 2.25 μg. g^{-1} and 12.84 ± 1.09 μg.g^{-}1, respectively (Table 10.8).

The association of *Hordeum vulgare* and the earthworm (*Lumbricus sp.*) showed an accumulation by *Hordeum vulgare* of 12.91% of soil lead and by *Lumbricus sp.* of 8.78% of soil lead (Fig. 10.2). The presence of earthworms reduced the phytoextraction of Pb by barley by 5.2% compared to the results found in the

Table 10.8 Descriptive statistics of lead concentrations (μg.g^{-1} DW) in the soil–plant–earthworms system

Attributes	*N*	Mean ± SD	Min	Max
Polluted soil				
Pb-soil	16	316.25 ± 87.24	150,00	430,00
Pb-barley	16	38.00 ± 5.68	31.00	50.00
Pb-EW	16	26.01 ± 6.66	16.53	39.00
Control soil				
Pb-soil	4	67.5 ± 9.57	60,00	80,00
Pb-barley	4	20.25 ± 2.25	17.00	23.00
Pb-EW	4	12.84 ± 1.09	11.36	13.93

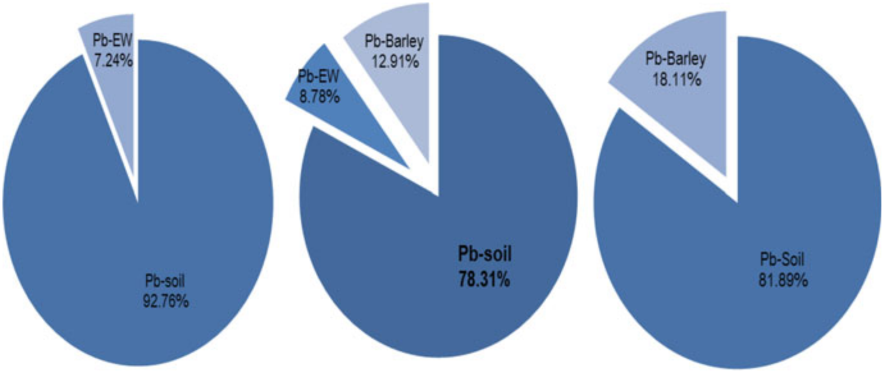

Fig. 10.2 Percentage of lead accumulated by barley and earthworms in soil–earthworms system, soil–plant system, and soil–plant–earthworms system

absence of earthworms and the concentration of lead in earthworms increased by 1.54%.

The bioavailability of metals in the soil influences their bioaccumulation (Brown 1995), and biotic and abiotic factors can influence this bioavailability in the polluted environment. Romheld (1986) and Hinsinger (2001) pointed out that the exchange activity of the root scan changes the pH. Furthermore, it is well known that earthworms strongly influence soil physical and chemical properties. Hence, the importance of considering their role in the bioavailability of metals is thus justified (Huynh 2009).

Soil characteristics can change the bioavailability of metals by modifying the speciation of metals and/or by modifying the adsorption of soil particles (Spurgeon and Hopkin 1996; Alloway 1995a, b; Van Gestel 1992). In theory, the decrease in the pH of a metal-rich soil should increase their bioavailability.

The presence of earthworms in the soil significantly lowers the pH (Cheng and Wong 2002; Huynh 2009; Yu and Cheng 2003; Boukirat 2018). The decrease in soil pH improves the phytoextraction process (Sanders et al. 1986).

However, other studies point out that earthworms increase the pH of the soil (Cheng and Wong 2002; Hu et al. 1998; Salmon 2001; Wen et al. 2006; Udovic and Lestan 2007). Except for the study of Lemtiri et al. (2016) on the earthworm *E. fetida,* who reported that the presence of the earthworm did not affect the pH values. These differences observed between the different studies may be due to the earthworms used (species, ecological category, etc.), the type of soil, and the different plants.

The activity of earthworms on the soil causes changes in soil physical and chemical properties. The association of both earthworms and plant in the same soil induces at a much lower pH than that observed when they are separated (Boukirat 2018). Soil pH is a crucial factor that affects adsorption and desorption behavior and therefore metals bioavailability in the soil, and it is important to assess the pH changes induced by the activity of earthworms (Lemtiri et al. 2016; Wen et al. 2004).

The pH is a factor whose role is crucial for the mobility of metal ions, because it influences the number of negative charges that can be dissolved (McLaughlin et al. 2000). Spurgeon et al. (2006) find that the solubility of metals and their speciation strongly depend on pH and that their accumulation in earthworms is influenced by their concentration in the soil and, in the case of Cd by pH.

The cause that may explain the limited effects of the change in pH on the tissue concentration of earthworms was explained by Oste et al. (2001) who suggested an effect of pH on absorption by the skin, and, on the other hand, the influence of soil particles ingested.

10.6.1 Lead Concentration in the Plant Between Presence/Absence of Earthworms

The presence of earthworms significantly affects the lead concentrations in the plant ($P < 0.001$) (Fig. 10.3) as the plant *Hordeum vulgare* accumulates more lead alone than in the presence of the earthworm *Lumbricus sp.* 59.44 ± 13.16 $\mu g.g^{-1}$ and 38.00 ± 5.68 $\mu g.g^{-1}$, respectively. The presence of earthworms reduced 5.2% phytoextraction of lead by barley compared to the results found in the absence of earthworms. The earthworm seems to retain a part of the lead by accumulating it and makes it less available for barley. A decrease in metal concentration of the plant *Leucaena leucocephala* which is cultivated in soil that contains earthworms was also observed by Sizmur and Hodson (2009). Earthworms can in certain situations decrease the availability of metals in polluted soils, which has been confirmed by some studies (Ma et al. 2000, 2006b; Liu et al. 2005; Lukkari et al. 2006; Duarte et al. 2012).

The decrease in lead concentrations accumulated by barley can be advantageous if taken from a health standpoint. The use of barley as a fodder plant and for human consumption represents a risk of bioconcentration of this metal in the food chain through direct or indirect way on human health.

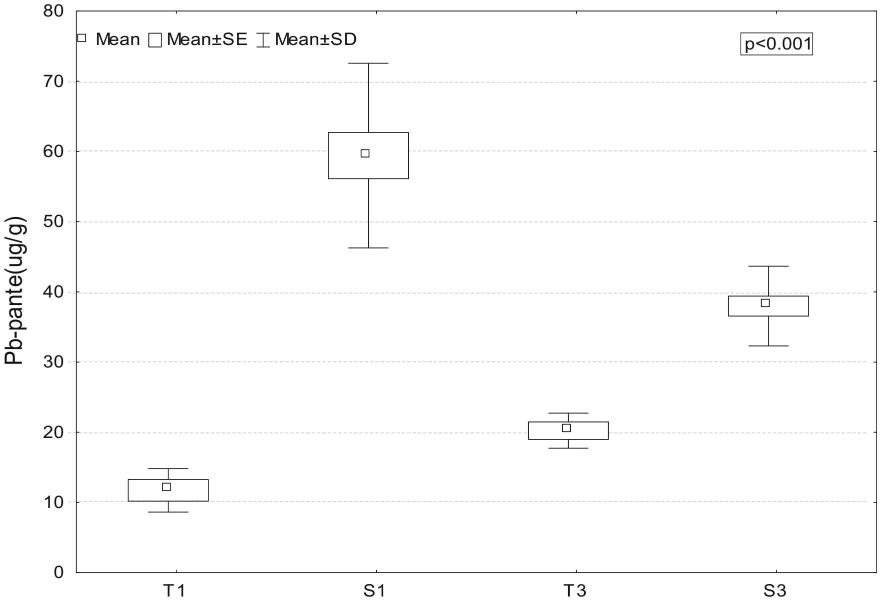

Fig. 10.3 Lead concentrations in the plant in the presence (S3-T3) and absence (S1-T1) of earthworms; **S1**: Plant + Pb polluted soil; **S3**: Plant + Earthworms + Pb polluted; **T1**: Plant + Unpolluted soil; **T3**: Plant + Earthworms + Unpolluted soil

10.6.2 Lead Concentration in Earthworms Between Presence/Absence of the Plant

The presence of the plant significantly affects lead concentrations in earthworms ($P < 0.001$) (Fig. 10.4). The concentrations recorded in earthworm tissue suggest that the presence of the plant *Hordeum vulgare* increases these concentrations by 1.54%, 26.01 ± 6.66 μg.g^{-1} in the presence of the plant against 24.01 ± 10.97 μg.g^{-1} in its absence. In contrast Lemtiri et al. (2016) found that the addition of *Vicia faba* or and *Zea mays* reduced Pb and Cd accumulation in earthworm tissues. Also Elyamine et al. (2018) reported a significant decrease in Cd concentrations of earthworms in the presence of plants.

Earthworms immobilize heavy metals by accumulating them in their bodies, making them less available to other soil organisms. They also reduce the toxicity of the soil (Eslami et al. 2019).

The impact of earthworm activities increases the availability of metals in contaminated soils (Wen et al. 2004; Coeurdassier et al. 2007; Udovic and Lestan 2007; Jusselme et al. 2013). Wen et al. (2004) observed that the earthworms increase the concentration of metal in plants. The earthworm *Pontoscolex corethrurus* increases also the bioavailability of Pb compared to soils without earthworms and enhances its absorption by the plant (Jusselme et al. 2012). In contrast Ma et al.

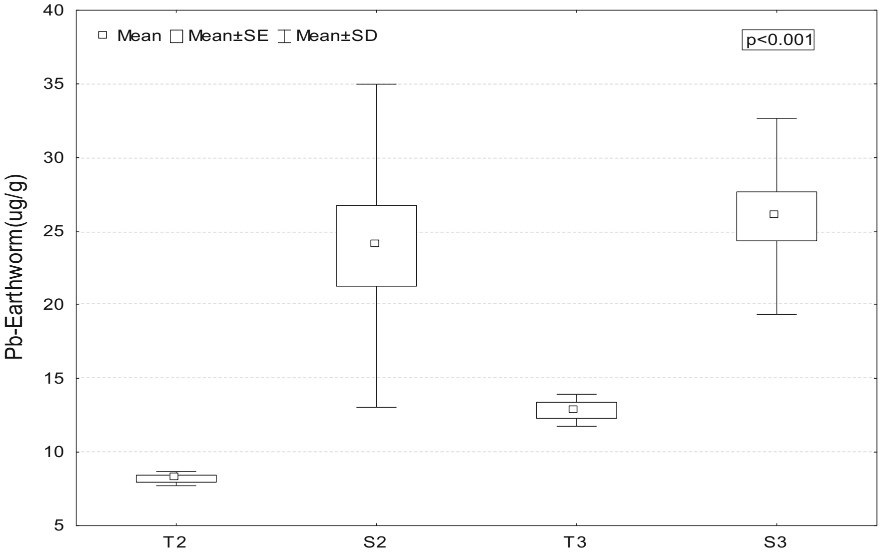

Fig. 10.4 Lead concentrations in earthworms in the presence (S3-T3) and absence (S2-T2) of the plant; **S2**: Earthworms + Pb polluted soil; **S3**: Plant + Earthworms + Pb polluted; **T2**: Earthworms + Unpolluted soil; **T3**: Plant + Earthworms + Unpolluted soil

(2006b) found that the effects of the earthworm *P. guillelmi* decreased the concentration of extractable Pb and Zn.

These different observations can be explained by a different impact depending on the earthworm, the plant, the metal and their interaction.

10.7 Role of Earthworms in Soil Sustainability

Soil is a fundamental and important element for the survival and the development of human beings (Qayyum et al. 2020). Soil sustainability is an important and complex challenge which is influenced by soil degradation and agricultural pollution (Zentner et al. 2004; Raj et al. 2019a, b). Soil management is crucial for improving productivity of crops and to maintain environmental sustainability (White et al. 2012). Studying the impact of earthworms on soil and plants is essential for understanding the biological functioning of soils and to support practices that are based on this functioning (Hedde 2018). Earthworms are very sensitive to their environment, that is why they are good bio-indicators of soil management (Paoletti et al. 1991).

Earthworms (annelids, oligochaetes) represent a major component of soil invertebrates which have a major impact on soil characteristics (physical, chemical, and biological), ensuring the maintenance of the soil's capacity to deliver ecosystem services (Lavelle 2002; Lavelle et al. 2006). They are also sensitive to the physical and chemical modifications of soil parameters (Paoletti et al. 1991).

The beneficial role of earthworms in soil sustainability and plant growth, and the amount of research done on them make them more promising for assessing the sustainability of the environment (Paoletti 1999).

Their importance for soils was first cited by Darwin: "*. . .the land was regularly ploughed and still continued to be thus ploughed by earthworms*" (Darwin 1881 in Pelosi 2008). He emphasized their role in soil formation, dynamics, and fertility (Brown et al. 2003a; Jana 2009).

Nowadays, earthworms are considered engineers of the terrestrial ecosystem (Jones et al. 1994); they change the availability of resources for other organisms (Pelosi 2008). Their populations vary from a few individuals in a square meter of soil to more than 1000 individuals (Edwards 2004 in Da Silva 2013).

Earthworms play an important role in their environment through various physicochemical and biological mechanisms, making it possible to improve fertility and preserve soil structure (Stork and Eggleton 1992; Lavelle et al. 1997) which is not without importance for the growth of the plant (Huynh 2009). Also, by affecting both physical and chemical properties of the soil (Edwards 2004) they modify the biotope of microbial communities (Lavelle and Gilot 1994; Lavelle et al. 1997). They also play a major role in the incorporation of OM in soils, the functioning of biogeochemical cycles, and the maintenance of favorable physicochemical conditions for plants and other soil organisms especially microorganisms (Brown et al. 1999, 2000; Lavelle 1988; Lavelle et al. 1998, 2006; Edwards 2004; Blouin et al. 2013; Da Silva 2013). The decrease in their activities in the soil can disrupt the recycling of OM (Cluzeau et al. 1987).

Earthworms play a key role in soils because they participate in the physical, chemical, and biological dynamics of the soil (Pelosi 2008; Singh et al. 2016). The absence of earthworms blocks OM on the surface; in fact their activity allows the fragmentation and mineralization of OM in the soil and therefore the recycling of nutrients and makes them more available to plants (Jana 2009; Brown et al. 2003b, 2004; Chauhan 2014; Datta et al. 2016).

Their main functions (Fig. 10.5) consist in: (1) Decomposition of OM (Datta et al. 2016) (2) The creation of galleries which improve the porosity and the aeration of the soil (Lavelle 1997; Fonte et al. 2009), the infiltration of water (Pelosi 2008; Datta et al. 2016) and facilitate root penetration (Jegou et al. 2002) (3) The excretion of dejection (deposited on the walls of the galleries) or turricules (discharges present on the ground surface) (Huynh 2009; Pelosi 2008). The successive passages of earthworms in the soil cover the galleries of mucus and excrement rich in nutrients (Sims and Gerard 1985; Binet and Curmi 1992; Huynh 2009), especially in nitrate (NO^{3-}), ammonium (NH^{4+}), and organic carbon (Bhatnagar 1975), thus promoting the development of a large bacterial microflora throughout the gallery walls, resulting in an increase in respiratory activities and enzymatic mineralization (Binet 1993; Huynh 2009; Fonte et al. 2009). The turricules also present higher concentrations of potassium, calcium, magnesium, phosphorus (Lavelle and Martin 1992).

However, earthworm impact on soil varies according to their ecological category. The endogens and the anecics are the most influential (Bouche 1977).

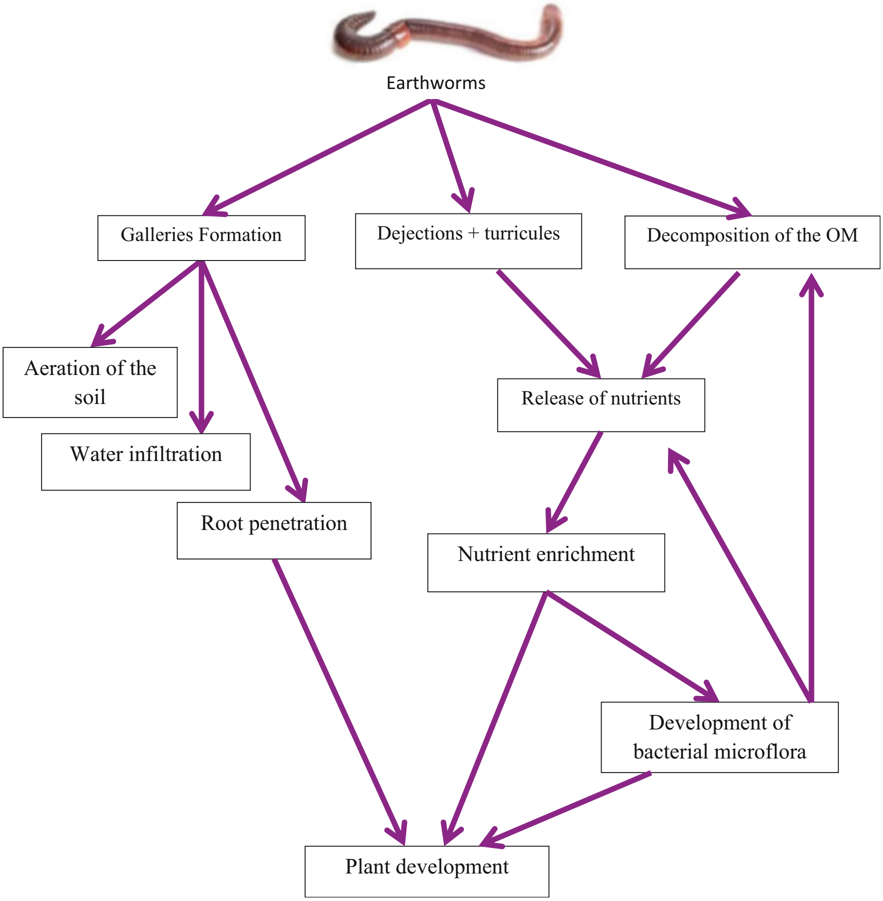

Fig. 10.5 Functions of earthworms in the soil

The class of epigeic described by Bouche (1977) concerns the earthworms living in the soil surface in organic heaps (manure, compost, leaf litter, bark). These earthworms due to their diet based on dead OM (fragments of plants, fungi) will be responsible for the decomposition and fragmentation of dead plant matter (Puga Freitas 2012; Da Silva 2013).

Anecics are large individuals, living in permanent vertical galleries which open on the surface (Bouche 1977). They are characterized by a strong activity in the soil, they feed on OM in an intermediate state of decomposition, and ensure its mixing with the mineral fraction of the different horizons of the soil (Huynh 2009; Da Silva 2013; Pelosi 2008; Puga Freitas 2012). Due to the construction of their galleries, they allow the development of hot spots rich in water and oxygen where the bacterial and fungal populations will be able to develop (Jana 2009). The anecics are sensitive to mechanical work on the soil and to inputs (Da Silva 2013).

The endogeic species (Bouche 1977) represent the most important group; they constitute 20–50% of the biomass of earthworms in the soil. Endogeics live permanently in the ground where they dig horizontal temporary galleries highly branched. They feed on the OM contained in the soil, and influence the soil microorganisms (Da Silva 2013; Huynh 2009; Jana 2009; Pelosi 2008). Endogeics spend the most time in the soil and are therefore likely to be most affected by soil contamination (Da Silva 2013).

Several studies have identified the effects of earthworms on plant growth and development (Scheu 2003; Brown et al. 1999, 2003b, 2004; Jana 2009). These studies have shown a positive impact on the aboveground biomass in 75% of the cases for tropical earthworms and 79% of the cases for temperate earthworms (Puga Freitas 2012). An augmentation in the biomass of aerial and root parts and in seed yield is also observed by Brown et al. (1999).

Earthworms participate in the release of substances such as vitamins and proteins that stimulate plant growth (Edwards and Bohlen 1996 in Pelosi 2008) and interactions with beneficial microorganisms (Jana 2009). PGPB (Plant Growth Promoting Bacteria) that synthesize substances similar to plant hormones, whose populations and activity increase in turricules (Pederson and Hendrikson 1993). The origin of these substances, produced indirectly by microorganisms associated with the digestive tract of earthworms or their structures (turricules, galleries) seems specific to the plant and earthworm species studied (Cluzeau et al. 2005).

Earthworms impact the activity and abundance of bacteria populations (Puga Freitas 2012; Jana 2009; Fonte et al. 2009) such as nitrifying and denitrifying bacteria (Wu et al. 2012; Parkin and Berry 1999; Businelli et al. 1984). The bacterial populations are involved in the solubilization and mineralization of inorganic phosphate (Rodriguez and Fraga 1999; Wu et al. 2012) as well as on the solubilization of potassium (Wu et al. 2012).

Several studies have also shown the effect of earthworms on reducing the severity of many diseases (Stephens et al. 1993, 1994; Stephens and Davoren 1995, 1997; Clapperton et al. 2001; Wolfarth et al. 2011). These effects are often associated with better plant nutrition or an earthworm predation effect (Puga Freitas 2012).

Earthworms play a central role in improving and maintaining the productivity of agro-systems. However, these organisms directly or indirectly suffer the consequences of soil management methods (Pelosi 2008). The level of their population is sensitive to cultivation techniques, the products that are applied, and the quality and quantity of the carbon resource, which are important characteristics of the sustainability of agro-systems (Bockstaller et al. 2008). Earthworms are considered to be practical indicators of soil fertility and the sustainability of agricultural systems (Richards et al. 2007; Moonen and Bàrberi 2008; Paoletti 1999).

10.8 Bioremediation and Agricultural Sustainability

Sustainable agriculture is a system of agricultural practices which aims to ensure the objectives of sustainable development, the management of agricultural lands must be able to offer the best possible production, durably, without harming the environment, the quality of the soil, and its long-term production capacity to meet the needs of future generations. Lal (1998) defines sustainable agriculture as the ability of agricultural systems to remain productive, efficiently and indefinitely.

The agriculture of tomorrow must be respectful of the environment without harming economic profitability (White et al. 2014), and must have as main concern better management of natural resources and preservation of soil and public health (Chowdhury et al. 2008; Khan et al. 2020a, b).

The soil is a complex and fragile ecosystem which represents a life support for most living organisms. Intensive agriculture, modern farming techniques, the use of pesticides, fertilizers, etc., deteriorate the soil and unbalance its proper functioning. The quality of the soil is thus threatened, and is in constant decline due to the overexploitation of the soil and the pollution generated by the excessive use of chemicals. The pollutants accumulate in the soil; contaminate surface and groundwater and the food chain. They can negatively affect soil biodiversity, plant growth and their production capacity.

The preservation of soil quality and biodiversity is fundamental to ensure a sustainable agricultural system (Datta et al. 2016; White et al. 2014). To preserve the soil it is necessary to have recourse to remediation methods which disturb the soil less and are able to maintain soil quality and biodiversity. Bioremediation is a decontamination technique which uses the capacity of certain living organisms as plants and bacteria, to accumulate or degrade pollutants. Bioremediation do not have environmentally harmful processes or negative impacts compared to other techniques (chemical or physical treatments) (Juwarkar et al. 2010). It is a safe and environmentally friendly method and cost effective. Its goal is to decontaminate the soil and improve its health (Purohit et al. 2018) and it has advantageous effects on soil fertility and structure (Juwarkar et al. 2010).

There are many methods of bioremediation and they can be divided into two categories: In situ bioremediation which involves the treatment of soil directly at the level of contaminated sites (Talley 2005; Azubuike et al. 2016). It is a less expensive method and less disruptive to the environment (Vidali 2001). The ex situ bioremediation which involves excavating contaminated soils from sites and moving them to another site for treatment. This method presents a risk of contamination of other sites (Purohit et al. 2018; Srivastava 2015; Azubuike et al. 2016). It can lead to health risks and safety risks due to the excavation and displacement of the contaminated soil (Juwarkar et al. 2010; Talley and Sleeper 2006).

Bioremediation is a good alternative for soil decontamination; however, its effectiveness depends on multiple factors, one of them is the pollutant. Not all the pollutants can be removed from soil; some of them are biodegradable or bio-transformable but pollutants such as heavy metals are persistent. Phytoremediation is a suitable technique for this type of pollutant which is an in situ *bioremediation* technique that uses plants capacity to bioaccumulate pollutants and is considered to be a major tool in bioremediation of heavy metals and sustainable agriculture (Belliturk et al. 2015).

Several researches made it possible to develop new methods of bioremediation to improve the capacity of remediation, among them the association of two organisms such as plant and bacteria. The use of combined technologies such as fertilized-assisted remediation (Sun et al. 2018) and transgenic organisms (Gerhardt et al. 2017) is important to develop in order to respond to the current and future need for remediation of polluted sites, and to ensure a healthy environment.

To ensure sustainable agricultural production, the soil must be preserved (its structure, quality, biodiversity, etc.) and not just decontaminated. Phytoremediation is a solution that meets the need to decontaminate the soil, preserve it, and maintain a healthy environment. However, the problem which arises for the rehabilitation of agricultural soils is that they are constantly used while these techniques take time and mobilize the land.

Sustainability cannot be achieved if agricultural practices overexploit agricultural ecosystems and abuse the use of chemicals (Saber 2001). Whatever the performance of the soil remediation techniques used and their effectiveness, the sustainability of agricultural systems cannot be reached without changing the current mode of exploitation of agricultural lands, the excessive use of chemicals, and if we do not opt for a more responsible and environmentally friendly soil management (sustainable management of soil).

10.9 Research and Development Activities: Case of Algeria

Bioremediation is an old concept that was used from the earliest civilizations to recycle water resources by exploitation of the marshes. However, the first installations which testify to the voluntary use of a wetland for water purification date from the end of the nineteenth century. Bioremediation has become a current trend due to its simplicity, efficiency, and safety (Singh et al. 2020).

In 1869, the work of Mille and Durand on the degradation of pollutants from wastewater by agricultural crops made it possible to set up in Paris one hectare of "model garden" open to the public in order to convince farmers of the benefits of this type of installation. In 1875, the cities of Moscow and Berlin set up similar treatment systems on an area of 25,000 ha for the Berlin region. In 1901, the city of San Antonio set up an artificial lake (Lake Mitchell) with an area of 275 ha with the aim of treating its wastewater (Boutin et al. 2000). At the same time, the city of Munich developed a similar project by installing a 233 ha water body to create a biological treatment plant. This technique makes it possible to reproduce the mechanisms of degradation, transformation, and recycling of OM thanks to the purifying properties of microscopic algae (Boutin et al. 2000).

Vascular plants floating or rooted (macrophytes) will not be involved in treatment until much later. Their depolluting effect has been known empirically for a very long time, but it was not until the 1950s that German researchers began to study this phenomenon scientifically. Dr. Kathe Seidel of the Max Planck Institute undertook the first scientific work followed by experiments using an artificial wetland pilot for the treatment of wastewater (Campbell and Ogden 1999). These works, presented for the first time in 1953, showed that certain plant species such as marsh rush (*Scirpus lacustris*) could have a real purifying activity. However, it was not until 1972 that the first functional station was built in Othfresen, Germany (Boutin et al. 2000). This process was introduced in France in the 1980s and one of the first installations, still in service today, was carried out in the commune of Pannissières in the Jura.

Since the 1970s, phytoremediation has been booming. The use of plants to eliminate, in particular, metallic trace elements and pesticides, is attracting growing interest and has been the subject of numerous studies. The nature of the pollutant and its accessibility for plants are decisive in the choice of the phytoremediation process to be used for optimal treatment.

In 2010 the Algerian Ministry of Higher Education and Scientific Research (General direction of scientific research and technological development) launched a national research program (NRP) and more than 2000 research projects have been selected by the intersectoral commissions including more than 80 thematic projects “Environment and Promotion of Sustainable Development.” These projects must contribute to the universal knowledge of science and contribute to a better classification of Algeria in the field of experimental and fundamental sciences. This program aims to strengthen research on the vulnerability issues of “biological systems” through a social and economic approach. The main objective is to reduce the cost of transfer of pollution control technologies, as well as taking charge of the management of the effects on populations and ecosystems. All this is in order to develop a national environmental policy within companies, and to develop their capacities for observation, forecasting, and scientific investigation.

From the numerous scientific works carried out by Algerian researchers, the use of plants, microorganisms, and macro-invertebrates as biological means of depollution and rehabilitation of soils contaminated by hydrocarbons and heavy metals becomes more and more encouraging.

The capacity of some species to tolerate and accumulate certain pollutants opened up new areas of research into soil treatment involving bioremediation. Among the current concerns in Algeria and in particular that of SONATRACH (Algerian petroleum company), soil pollution by petroleum derivatives which are one of the principal sources of pollution in the region, the development of a biological treatment for contaminated soils is a well-founded and promising solution, which will allow real management of soil pollution at affordable costs. For this purpose, several studies have been carried out, among them: Ferradji et al. (2014) who studied the degradation of petroleum and naphthalene by *Streptomyces* spp. in the surface soils of the Mitidja plain (North of Algeria); Meliani and Bensoltane (2016) on the application of *Pseudomonas* biofilm in the absorption of heavy metals; and Hamoudi-Belarbi et al. (2018) on the potentials of biostimulation of carob croquettes and carrot peel waste, for the bioremediation of soils polluted by crude oil.

Benchouk and Chibani (2017) also showed that the bioremediation of artificially contaminated soils by bacterial strains and the consortium showed a very great effect on the degradation of hydrocarbons. They also carried out mutagenesis on the strains: *Candida sp., Bacillus sp.,* and *Pseudomonas putida*. To improve the degradation of hydrocarbons on soil samples from the Arzew oil refinery (West Algeria), which showed that the mutagenesis of strains developed a greater or reduced capacity for degradation of petroleum and diesel (*Pseudomonas aeruginosa* representing the highest capability of degradation with 80.86% of hydrocarbons biodegradation).

Heavy metals from road traffic also represent a major source of soil contamination. The study of Maatoug et al. (2013) showed that barley has the capacity to decontaminate the soil located near the highways of the Tiaret region (West Algeria).

Soil remediation aims to preserve soil health and sustainability and to protect the organisms (flora and fauna) that live there as well as humans, by protecting one of the most important resources (the soil) that provides various services. The aim of soil remediation is also to reduce the transfer of pollutants to the groundwater and their bioconcentration in trophic networks (biomagnification). Physicochemical depollution methods have several disadvantages: they are expensive and difficult to implement (Gadd 2000; Salt et al. 1995; Raskin et al. 1994). Further, they strongly disturb the biological activity of soils and alter their physical structure (Huynh 2009). For this purpose, biotechnologies (bioremediation, phytoremediation) seem to be an interesting alternative, these techniques are more respectful of the environment, preserve the characteristics of the soil, and inexpensive.

It should be noted that understanding the biogeochemical processes related to the bioremediation of polluted soils requires a multidisciplinary approach based on both analytical (identification and monitoring of contaminants, modification of soil quality) and biological aspects. This last point implies in-depth knowledge both at the soil level (identification and monitoring of microorganisms of interest which are involved in bioremediation) and at the plant level (characterization of molecules exuded at the rhizospheric level, adaptation and monitoring of plant growth).

10.10 Policy Strategy and Legal Framework for Soil Protection in Algeria

Since the end of the nineteenth century, the industrial sector has grown without concern for the release of toxic elements into the soil. In fact, soil has long been considered a renewable resource, even inexhaustible on the scale of human generations, capable of receiving without consequence rejections from our activities. We now know that the soils are characterized by a fragile and vulnerable balance. Today, this heritage is threatened both by the heavy heritage of the past and by the extension of the areas devoted to industrial development (Lecomte 1998).

In Algeria, agriculture is subject to other physical constraints which burden its natural potential and weigh on the ecological balance of the different natural regions. Indeed, despite the efforts made by the State in the fields of water and soil conservation, soil erosion and pollution continues to increase and water resources are seriously affected by overexploitation or salinization. Desertification is a threat to the 32 million hectares of rangelands and the forest cover of northern Algeria is permanently exposed to natural risk (fire) or to anthropogenic pressure (deforestation-clearing).

In this context, Algeria has implemented, since the 2000s, a policy aimed at improving national food security, the development of certain priority agricultural sectors and land development, including the National Agricultural Development Program (Bessaoud et al. 2019).

The commitment of the Algerian government, for a rational management of natural resources is evident, having regard to the strengthening of the legislative and institutional framework and to the numerous programs launched in the field of environmental education, promotion of renewable energies, fight against poverty, protection of soil and biodiversity, and this, integrated in a three-dimensional approach combining economic, social, and environmental considerations.

The 2010–2014 programs are part of this sustainable development approach and strengthen the intersectoral and participatory approach to planning and implementing integrated natural resource management. It allows the management of issues related to the preservation and sustainable use of biodiversity, soil degradation, water management, and/or the stabilization of greenhouse gases in the atmosphere (National Report of Algeria 2011). Indeed, law No. 83-03 on environmental protection (1983) aims to implement a national environmental protection policy aimed at: protecting, restructuring, and enhancing natural resources, soil conservation/soil improvement (Algerian official journal, www.jordp.dz).

In terms of thinking for the future, the improvement, in practice, of the integrated management of natural resources, in particular the soils affected by pollution, would require significant changes in approaches and interventions, which should be based on more coherent and effective legal and institutional arrangements. Successful water and soil conservation measures also require removing barriers to long-term investment. Without land and financial security, can the farmers concerned engage in long-term activities to maintain soil fertility? This should also call for greater integration of environmental policies (forests, waters, soils, biodiversity, etc.) and agricultural and rural development (Plan Bleu 2003).

10.11 Conclusion

Earthworms play an important role in the soil through various mechanisms, physicochemical and biological, which improve fertility and preserve soil structure and therefore its sustainability. Their proposal as a means to improve the phytoremediation efficiency can be beneficial for maintaining soil fertility and its rehabilitation. Several studies report the effectiveness of the earthworm/plant association for soil remediation, on the one hand, by increasing the bioavailability and phytoextraction of metals, and, on the other hand, by increasing plant biomass. The interaction between these two organisms differs from one species to another (plant and earthworms).

The activity of the earthworm *Lumbricus sp.* reduces the bioaccumulation of lead by *Hordeum vulgare* by 5.2%, and the concentrations recorded in earthworm tissue suggest that the presence of the plant increases these concentrations by 1.54%. The use of another species of earthworm (for example: an eco-physiologically different species) can have a different impact on the phytoextractor behavior of the barley, hence the interest in extending these studies to other species. This study highlights the influence of earthworm activities on the bioaccumulation of lead by barley but also that of the plant on earthworms. The introduction of earthworms into polluted soils represents a great advantage for maintaining soil quality and better remediation; large-scale inoculations of earthworms can be imagined in the soil to improve soil fertility and sustainability. The potential of earthworms must be fully studied for better sustainable soil management.

10.12 Future Perspective

This research opens up many perspectives in the field of phytoremediation and in other fields. Complementary works to this study are envisaged; study the evolution of the earthworm populations in different soils for a better understanding of their behavior towards pollution and cultural practices. Further, study on the physiology and biochemistry of barley to better understand the effect of earthworm activity on this plant and the mechanisms involved in its response. Also a study of the impact of earthworms on the evolution of bacterial communities in metals polluted soils which play a role in the availability of metals for plants needs to be explored.

A study on the possibility of increasing earthworm population in the soil or of introducing them on a large-scale is to be considered to improve soil fertility and durability.

On the other hand, these bioremediation tools have indeed become essential to guide the policy of soil remediation for sustainable agriculture. However, bioremediation studies are still too ad hoc and limited to meet all of the needs.

The industrial and socio-development of Algeria has not always taken into account its impact on the quality of the environment and on the conservation of the environment and natural resources. However, from the year 2010, this gap was filled by the definition and the implementation of a policy of environmental protection, and in particular of fight against the pollution of agricultural soils, aiming in particular at:

- The creation of a multidisciplinary research network in a context of sustainable development,
- Determining the impact of certain micro-pollutants whose concentrations in the soil are difficult to quantify directly,
- Raising public awareness, in particular farmers about soil pollution,
- The development of a preservation strategy with regard to soil pollution in agricultural land,
- Exchange of experiences in the field of bioremediation of soil pollution.

It is crucial to assess the threats linked to soil pollution and to identify contaminated sites in order to remediate them and to ensure soil sustainability.

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