Phytotechnologies for Site Remediation

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Abstract

Phytotechnologies for inorganic contaminants include phytoextraction, phytostabilization, phytotransformation, and phytohydraulics. Soil amendments may be added to increase contaminant solubility when phytoextraction is implemented. For phytostabilization soil amendments may be added to reduce contaminant availability, such as transformation to a less soluble compound. Phytotransformation is the process of changing the contaminant to another form to reduce risk of movement or toxicity. Phytohydraulics may be applied with phytostabilization when the design includes evapotranspiration to reduce transport of the contaminants away from the point of contamination. Plants used for phytostabilization should be able to grow well in the contaminated soil, produce a product of value and commercial interest, and evapotranspire sufficient water to achieve containment of the contaminants. The uptake and translocation of the contaminants to aboveground biomass should be small enough to allow the plant biomass to be used for a commercial purpose. *Miscanthus* is among the most promising energy crops for phytoremediation: it grows well in contaminated soil, evapotranspires large quantities of water, and produces high-quality cellulose. The use of soil amendments can help to minimize contaminant uptake and improving soil quality is an important issue. Several other energy crops that have good potential for phytostabilization application are introduced in this chapter as well.

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2.1 Introduction

Phytoremediation technology was established as an environment-friendly concept to restore polluted sites before 1990, and a year later the term was used. Generally, phytoremediation technology can be divided into six subtypes depending on the contaminant origin and the mechanisms of restoration (USEPA, 1998). In order to remediate sites polluted by contaminants of inorganic origin (mainly trace elements) the following processes are proposed (USEPA, 1998):

1. phytoextraction – remediation mechanism is based on the uptake of contaminant by roots and its transmigration to the aboveground tissues (leaves, stems, branches);
2. rhizofiltration – remediation mechanism is represented by the accumulation of contaminants in roots;
3. phytostabilization – remediation mechanism is based on the contaminant immobilization in soil by plant root exudates.

In case of remediation sites polluted by contaminants of organic origin the following processes are in the focus (USEPA, 1998):

4. phytodegradation – remediation mechanism is based on absorbing the contaminants by roots and converting them by plant enzymatic activity to safe compounds;
5. rhizodegradation – remediation mechanism is based on the provision of favorable environmental conditions for microorganisms to

be able to degrade the contaminants in the rhizosphere, plant roots release organic compounds (nutrients, enzymes, organic acids, etc.) to reach favorable conditions;

6. phytovolatilization – remediation mechanism is based on absorbing the contaminants by roots and releasing them to atmosphere.

The term phytotechnologies, which replaces the earlier term phytoremediation, is also known as green-remediation, and in general, means using plants to degrade, extract, contain, transform into less harmful forms, or immobilize contaminants in soil, water, or air with inorganic or organic compounds. Phytotechnology mechanisms and technological effects are summarized in Table 2.1. Some phytotechnologies have gained public acceptance compared to other remediation techniques and multiple related terms, such as phytomanagement, have been introduced. As far as phytomanagement is concerned, this concept is newer and covers economic benefits (Robinson et al., 2009). In addition to using plants to reduce the risks posed by soil contamination, the concept

TABLE 2.1

Phytotechnology Mechanisms and Effect of Technology

Effect of Technology	Phytotechnology Mechanism	Definition
Reduce contaminant concentration (extraction, degradation)	Phytoextraction/ Phytomining/ Phytoaccumulation	The removal of inorganic contaminants from the soil through plant uptake, and subsequent harvest and removal of biomass. Phytoextraction, phytomining, or phytoaccumulation are typically used to remove metals from the soil (e.g., As extraction by <i>Pteris vittata</i> (brake fern) (Ma et al., 2001); Ni by <i>Alyssum</i> species (Li et al., 2003).
	Phytodegradation/ Phytotransformation	The breakdown of contaminants by the metabolic processes in a plant. Also includes the breakdown of contaminants in the soil by enzymes or other products produced by the plant. Primarily used for organic contaminants.
	Rhizofiltration/ Rhizodegradation	The breakdown or degradation of organic contaminants in the soil. The contaminants are either adsorbed onto the root surface or are absorbed by the plant roots. Due to enhanced microbial activity in the rhizosphere (the zone of soil influenced by the roots), the contaminants are broken down. This process can be enhanced by fertilization.

(Continued)

TABLE 2.1 (Continued)

Phytotechnology Mechanisms and Effect of Technology

Effect of Technology	Phytotechnology Mechanism	Definition
Reduce contaminant bioavailability without reducing total concentrations (immobilization)	Phytovolatilization	The uptake of contaminants by plants and release them into the atmosphere as they transpire water (direct phytovolatilization). Contaminant is removed from the soil and may be degraded as it moves through the plant’s vascular system before final removal from the system. This can be used for both organic (e.g., volatile organic compounds) and inorganic contaminants (e.g., Se, and Hg). Additionally, contaminants can be volatilized from soil due to plant root activities (indirect phytovolatilization) (Limmer & Burken, 2016)
	Phytosequestration/ Phytostabilization	This process sequesters, or reduces, contaminant bioavailability through precipitation or immobilization of contaminants in the soil, on the root surface, or within the root tissues (Laperche et al., 1996).
	Phytotransformation (inorganics)	The transformation of contaminants by the metabolic processes in a plant. It also includes the transformation of contaminants in the soil by enzymes or other products produced by the plant. This can be used for nutrients and other inorganic contaminants.
Reduce contaminant movement (containment)	Phytostabilization (Phytorestoration, In place inactivation)	Plants are used to stabilize contaminated soils or sediments, thus protecting them from transport by wind or water erosion. The main function is to contain the contaminated material. However, this is usually combined with adding soil amendment to reduce contaminant movement in soil (e.g., phytostabilization of Pb contaminated military site soil using <i>Miscanthus</i> in combination with P amendments (Alasmary et al., 2020)).
	Phytohdraulics	This process is used to limit the movement of contaminants with water. Plants are used to increase evapotranspiration, thereby controlling soil water and contaminant movement. This mechanism contains the contaminant by modifying site hydrology to reduce the vertical or horizontal movement of water in the soil (Narayanan et al., 1999).

includes converting the obtained biomass into useful products (Evangelou et al., 2015; Robinson et al., 2009); in other words, “phytomanagement is a combination of phytoremediation and sustainable site management with economic return” (Conesa et al., 2012; Pandey & Bajpai, 2019).

The goal of this section is to provide an overview of various plant-based techniques for remediation of contaminated soils and to introduce research and applications of plant cultivation in contaminated areas to obtain biomass, with emphasis on *Miscanthus* as the phytoagent (Pidlisnyuk et al., 2014).

2.2 Phytotechnologies

The two most commonly used phytotechnologies for inorganic contaminants are phytoextraction and phytostabilization. In the phytoextraction process the plant’s ability to accumulate trace elements is important. Based on the relative uptake and bioaccumulation potential, plants can be grouped into three categories: excluders, indicators, and accumulators (Adriano, 2001; Hunt et al., 2014) (see Figure 2.1).

The ability of plants to accumulate trace elements from the soil can be estimated by the enrichment coefficient (EC) or the bioconcentration factor, which are expressed as the ratio of defined trace element concentrations in the plant material (mg kg^{-1} of dry matter) and in the soil (mg kg^{-1} of dry soil). In addition, translocation factor (TLF) value reflects the levels of plants’ phytoextraction potential accounting as a ratio of the contaminants’ concentrations in the aboveground biomass to their concentration in roots

FIGURE 2.1

Three groups of plant categories based on their uptake behavior of trace elements: excluders, indicators, and accumulators. (Modified from Hunt et al., 2014.)

(Baker, 1981; Mamirova et al., 2020). Malayeri et al. (2008) and Zgorelec (2009) grouped plant species according to their ECs uptake capacities related to trace elements and sensitivity to trace element contamination as follows:

- high-accumulator plants EC 1–10
- medium-accumulator plants EC 0.1–1
- low-accumulator plants EC 0.01–0.1
- nonaccumulator plants EC < 0.01

The sensitivity or tolerance of plants to excess trace elements depends on plant species and their genotypes. Even among crops, sensitivity varies widely (Adriano, 2001). Excluders are tolerant to high-trace elements concentrations and their tolerance is achieved by preventing the absorption and translocation of toxic elements to aboveground biomass. However, the observed concentrations in the root are lower than those in the soil. These species have low potential for metal extraction, and EC value is less than one (Lasat, 1999). They are insensitive to trace elements over a wide range of concentrations, and a common example is various grass species. Indicators are plant species sensitive to trace elements and consequently certain symptoms can be manifested. Such plants are not tolerant to high concentrations of trace elements, and examples are grain and cereal crops (Adriano, 2001). Accumulators are plants which accumulate trace elements in various concentrations, however, in concentrations which are still lower than in case of hyperaccumulators. Hyperaccumulation is a specific characteristic inherent in certain species. The majority of hyperaccumulators are endemic plants which grow in soils rich in trace elements and behave like strict metallophytes (Baker & Brooks, 1989), where certain facultative metallophytes can survive in soils poor in the trace elements (Rascio & Navari-Izzo, 2011). These plants have developed special mechanisms for element uptake and tolerance to high concentrations. The mechanisms are genetically conditioned because the plant tissues do not manifest toxicity symptoms typical in plants due to high element concentrations. For successful hyperaccumulation the concentrations of the trace elements in the above-ground biomass have to be extremely higher compared to their content in the soil (Pulford & Watson, 2003). The negative aspect of hyperaccumulators is low biomass yield.

2.3 Phytostabilization of Arable Land Contaminated with Trace Elements

Phytostabilization uses plants to reduce contaminated soil material movement via water or wind. The approach is commonly used in combination with soil amendments to reduce contaminant bioavailability and to assist plant growth.

The term “bioavailability” is defined as the fraction of an element in soil which is available for absorption by humans, animals, or plants. In the processes of *in situ* inactivation or chemical stabilization the appropriate soil amendments are used for immobilization of contaminants in soil (Attanayake et al., 2014; Berti & Cunningham, 1997; Brown et al., 2003; Defoe et al., 2014; Hettiarachchi et al., 2000). Contaminant immobilization is achieved through enhanced sorption in soil, absorption and accumulation in roots, adsorption to roots or precipitation within the root zone, and physical stabilization of soils (USEPA, 2000). Phytostabilization assisted with soil amendments can also support re-establishment of vegetation at contaminated sites lacking native grasses because of high concentrations of phytotoxic trace elements or poor soil characteristics, i.e., low pH and poor agrichemical and physical characteristics (Gudichuttu, 2014; Solís-Dominguez et al., 2012; Tordoff et al., 2000; Wijesekara et al., 2016). Phytostabilization is recommended when other remediation approaches are not feasible due to extended contaminated area. It is also useful in case of limited funds for another remediation technique. The advantages of phytostabilization are low cost, simple implementation, and aesthetic aspects (Berti & Cunningham, 2000). The disadvantages are as follows: needs a long period (usually 30–40 years) for restoration of the certain area, problems connected with disposal of contaminated biomass, limited development of root system, seasonal and climate dependence.

There are two types of plants suitable for a phytostabilization process. One group is formed by plants tolerant to high concentrations of contaminants, i.e., trace element excluders. Another group is represented by species with highly developed root systems that can immobilize contaminated substances through uptake, precipitation, or reduction. In this case rather often relevant contaminants are concentrated in the roots and only a small portion of contaminants can move to the aboveground part of the plant.

Careful selection of plant species is the determining factor for the success of phytostabilization. Plant characteristics and soil properties are both important for proper selection of the most suitable phytoagent. Native species which can survive in targeted contaminated soil are made a preferred choice in many phytostabilization processes (Solís-Dominguez et al., 2012). In addition, the plants appropriate for phytostabilization are grasses and fast-growing plants which can provide sufficient coverage with developed root systems to stabilize trace elements. Selected plants should be simple for further maintenance after establishment.

2.4 Bioenergy Crops and Phytostabilization Options

Bioenergy crops are promising candidates for phytostabilization of soils contaminated with trace elements due to their good ability to grow in contaminated and marginal soils (Pidlisnyuk et al., 2014). Below the main energy

crops proposed for application in phytoremediation process are characterized. It should be noted here that for the same energy crop, different results have been observed. Differential response is due to multiple reasons, such as soil type, soil amount (for example, small pot studies with insufficient amount of soil), nature of soil contamination (field contaminated versus trace element spiked soils, aged versus not aged, or fresh), and cleaning methods employed for plant materials (i.e., inability to remove surface contaminations).

Arundo donax L. (Giant reed, Figure 2.2) is a perennial, tall, and upright grass with highly efficient C_3 photosynthesis. It belongs to the *Poaceae* family. The origin of Giant reed is not yet accurately defined; however, it is believed to be native from Asia or the Mediterranean basin. The plant is tolerant to

FIGURE 2.2

Arundo donax, Manhattan, KS Nov 2020. Photo by Lawrence Davis.

unsuitable growing conditions, yet showing best growth in areas with good access to water (Angelini et al., 2005). Giant reed is cultivated well in moderate, subtropical, and tropical areas of both hemispheres (Herrera & Dudley, 2003). It grows between 6 and 8 m high, while in ideal conditions the height can exceed 10 m. It is a promising crop for energy production in the Mediterranean climate in Europe and Africa. The advantage is that the crop is adapted to long drying periods (Jeguirim & Trouvé, 2009; Zema et al., 2012). Plantings can last 12–15 years and may annually produce up to 60 t of dry biomass ha⁻¹ in Central and Northern Italy (Angelini et al., 2005; Pilu et al., 2013). A considerable amount of research is reported in Table 2.2 about phytoremediation potential of *A. donax* in a variety of contaminated soils; however, results are mixed.

Panicum virgatum L. (Switchgrass) (Figure 2.3) is an upright, coarse, perennial C₄ grass. It belongs to the *Poaceae* family and originates in North America and Canada. The plant can be produced over an extensive geographic range, and the annual harvested biomass is up to 25 t of dry matter ha⁻¹ (Parrish et al., 2012) while stem can grow up to 2.7 m. Switchgrass develops well in marginal soils and shows good results in both fine and coarse textured soils (Rinehart, 2006). The recommended seeding rate is 200–400 germinating seeds m⁻². Usually, the amount of seeds for one ha varies from 4 to 10 kg ha⁻¹ (Moser & Vogel, 1995; Teel, 2003; Vassey et al., 1985; Vogel, 1987, 2000; Wolf & Fiske, 2009). Currently cultivation of switchgrass uses mainly hybrids. Some studies with trace elements are reported in Table 2.3.

TABLE 2.2Phytoremediation Potential of *Arundo donax* L. to Different Trace Elements

Trace Element	Phytoremediation Potential	Reference
Cd	Rhizofiltration in hydroponics Phytoextraction Uptake potential from the media	Düřešová et al. (2014); Sagehashi et al. (2011) Barbafieri et al. (2011); Chierchia, (2011); Sabeen et al. (2013); Yang et al. (2012) Papazoglou et al. (2005); Papazoglou et al. (2007)
Cr	Accumulator	Fiorentino et al. (2013); Kausar et al. (2012)
Cu	Phytoextraction Rhizofiltration	Chierchia (2011); Elhawat et al. (2014) Bonanno (2012)
Hg	Uptakes and accumulates Hg in roots	Bonanno (2012)
Ni	Uptake potential from the media	Bonanno (2012); Papazoglou et al. (2005); Papazoglou et al. (2007)
Pb	Not efficient in removing Pb from the media Certain genotypes have phytoextraction potential; others are excluders	Barbafieri et al. (2011); Bonanno (2012) Sidella (2014)
Zn	Phytoextraction in hydroponics	Düřešová et al. (2014)

FIGURE 2.3
Switchgrass, (*Panicum virgatum*) courtesy of Professor John Dolman, K-State.

TABLE 2.3
Phytoremediation Potential of *Panicum virgatum* L. to Different Trace Elements

Trace Element	Phytoremediation Potential	References
Cd	Rhizofiltration	Abe et al. (2008); Chen et al. (2008); Sankaran & Ebbs (2007) Gerst (2014); Juang & Lee (2010) Chen et al. (2012)
	Phytoextraction	
	Accumulator	
Cr	Phytoextraction in hydroponics	Chen et al. (2012) Shahandeh & Hossner (2000) Li et al. (2011)
	Potential remediator	
	Rhizoextraction	
Hg	Not efficient	Gerst (2014)
Pb	Excluder	Gleeson (2007) Johnson (2014) Żurek et al. (2013)
	Favorable for phytoremediation	
	Not efficient as accumulator	
Zn	Accumulator	Chen et al. (2012)
	Favorable for phytostabilization	

Pennisetum purpureum Schum. (Napier grass or Elephant grass) is a dense rhizomatous perennial C₄ grass which is often crossed with *P. americanum* to obtain a hybrid with better properties (Figure 2.4). It belongs to the *Poaceae* family and originates from sub-Saharan Africa; currently, it is widespread in tropical and subtropical regions. This species prefers areas with high precipitation; however, it also tolerates dry conditions due to a well-developed vigorous root system. The best growth is reported for deep, fertile loams, although it grows well on more marginal lands. *P. purpureum* is an aggressive grass able to grow rapidly, colonize new areas, and form dense thickets; moreover, the species is recognized globally as a very invasive grass. *Pennisetum purpureum*

FIGURE 2.4

Pennisetum purpureum Schum (Elephant grass).

grows forming thick clumps up to 1 m in diameter, with stems branched above, reaching 4–7 m height. Leaf length and width are around 100–120 cm and 1–5 cm, respectively (CABI, 2014). This plant can be used as a source for cellulosic bioenergy, fodder, cover material, bedding, and paper (Adekalu et al., 2007; Kabi et al., 2005). Positive results were recorded when it was used for treatment of waste sludge (Dhulap & Patil, 2014) and soil contaminated by hydrocarbons (Ayotamuno et al., 2006). Phytoremediation potentials of elephant grass for different trace elements are reported in Table 2.4.

Sida hermaphrodita L. Rusby (Virginia mallow) is a C_4 honey plant species (Figure 2.5) which belongs to *Malvaceae* family (mallows); it originated in North America. During the 1930s the plant was introduced to former USSR, and currently it can be found in all parts of Europe. Virginia Mallow is tolerant to extreme types of continental climate and can survive in cold conditions

TABLE 2.4
Phytoremediation Potential of *Pennisetum purpureum* Schum. to Different Trace Elements

Trace Element	Phytoremediation Potential	References
Cd	Rhizofiltration	Lotfy et al. (2012)
	Phytoextraction	Abdel-Salam (2012); Zhang et al. (2010)
	Accumulator	Ogunkunle et al. (2014)
Cr	Excluder	Lotfy & Mostafa (2014)
	Accumulator in humid conditions	Ogunkunle et al. (2014)
Cu	Excluder	Ogunkunle et al. (2014); Yang et al. (2010)
Pb	Excluder	Xia (2004); Yang et al. (2010)
	Accumulator	Ogunkunle et al. (2014)
Zn	Excluder	Ogunkunle et al. (2014); Zhang et al. (2010)

FIGURE 2.5
Sida hermaphrodita a perennial dicot used for forage, or biomass production. With two harvests per year it can serve for biogas production with a total annual harvest exceeding 26 Mg/ha. This photo, courtesy of Professor Marek Bury, ZUT, Szczecin, Poland, shows regrowth after a first harvest, alongside the crop maturing with flowers.

(even without snow at temperatures below -20°C) and dry conditions if the average annual precipitation ranges between 400 and 500 mm. Height in full maturity varies from 1 to 4 m, commonly reaches about 3 m (Borkowska & Molas, 2012). Its life span is about 25 years (Kasprzyk et al., 2013), the annual yield ranges from 15 to 20 t of dry matter ha^{-1} when cultivated in clay loam soils (Borkowska, 2007). In case of unfavorable conditions, the cultivation is often provided with the addition of sewage sludge; in this condition yield ranges from

none to 11 tons of dry matter ha⁻¹ (Borkowska & Wardzinska, 2003). The well-developed root system allows it to efficiently use limited nutrients and water from marginal soils (Borkowska & Wardzinska, 2003). *S. hermaphrodita* grows well in stony or sandy soil with high yields, and best growth is reported for moderately humid areas. Hybrids and cultivars are mainly cultivated now because they have higher yields than the original species. The data about phytoremediation potential of Virginia mallow are summarized in Table 2.5.

Sorghum × drummondii Steud. (Sudan grass) is an annual, warm-season, fast growing plant (Figure 2.6), which belongs to *Poaceae* family and is a hybrid of *S. bicolor* and *S. arundinaceum*, and possesses C₄ photosynthesis. Sudan grass is originally from Southern Egypt and Sudan; in 1909 it was imported to the US where it began to be grown as a fodder species. The crop is widespread in South America, Australia, South Africa, Central and Northern Europe. It shows best growth in areas with average annual precipitation between 600 and 900 mm, nevertheless tolerates drought periods, and can be produced in all soil types (FAO, 2012). Recently *S. drummondii* has attracted interests due to its ability to remove trace elements from different media (Table 2.6). According to Pivetz (2001) it can absorb and accumulate Co. Application of microbial inoculants improved the remediation process (Shim et al., 2014). Utilization of certain mycorrhizal fungi which form a symbiosis with *S. × drummondii* can increase the accumulation of trace elements from the contaminated soil (Gaur & Adholeya, 2004).

The *Miscanthus* genus belongs to the *Poaceae* (or grasses) family (Figure 2.7). It has C₄ photosynthesis with high water and nutrient-use efficiency and cold tolerance (Chung & Kim, 2012). The genus can be found within high lawns of

TABLE 2.5

Phytoremediation Potential of *Sida hermaphrodita* L. to Different Trace Elements

Trace Element	Phytoremediation Potential	References
Cd	Phytoextraction	Ociepa (2011)
	Rhizofiltration	Antonkiewicz & Jasiewicz (2002)
	Potential accumulator	Borkowska et al. (2001); Krzywy-Gawrońska (2012)
Cr	Efficiently removes Cr from the media	Borkowska et al. (2001)
Cu	Efficiently removes Cu from the media	Borkowska et al. (2001)
	Rhizoextraction	Antonkiewicz & Jasiewicz (2002); Krzywy-Gawrońska (2012)
Ni	Efficient in phytoextraction	Krzywy-Gawrońska (2012)
	Rhizoextraction	Antonkiewicz & Jasiewicz (2002)
Pb	Phytoextraction	Krzywy-Gawrońska (2012)
	Accumulator	Kocoń & Matyka (2012)
Zn	Phytoextraction	Krzywy-Gawrońska (2012)
	Accumulator	Borkowska et al. (2001)

FIGURE 2.6
Sudan-Sorghum forage hybrid at the USDA Plant Materials Center, Ashland Bottoms, Manhattan, KS, August 2013. Photo courtesy of Mark Janzen, Natural Resources Conservation Services, USDA.

TABLE 2.6
Phytoremediation Potential of *Sorghum × drummondii* Steud. to Different Trace Elements

Trace Element	Phytoremediation Potential	References
Cd	Excluder Rhizoextraction	Angelova et al. (2011); López-Chuken and Young (2005); Zwonitzer et al. (2003) Da-lin et al. (2011)
Cu	Excluder	Angelova et al. (2011); Tari et al. (2013)
Pb	Suitable for phytoremediation Chemically induced remediation Excluder	Murányi and Ködöböcz (2008) Zhuang et al. (2009) Angelova et al. (2011)
Zn	Excluder	Angelova et al. (2011)

Eastern Asia, from tropics and subtropics to Pacific islands, warm temperate regions, and subarctic areas. Wide adaptability to various environmental factors makes *M. × giganteus* a sterile triploid hybrid of *M. sinensis* and *M. sacchariflorus*, suitable for cultivating in different European and Northern American climatic conditions (Greef & Deuter, 1993, See Chapter 5 for further information about breeding of various hybrid Miscanthus and different species properties). Plant biomass annual yield ranges from 8 to 45 t dry biomass ha⁻¹ (Bilandžija, 2015; Heaton et al., 2008; Lewandowski et al., 2000; Maughan et al., 2012; Miguez et al., 2008) with long sustainable productivity

FIGURE 2.7

Miscanthus at Fort Riley, site, KS. USA. (Photo: Zafer Alasmary, Kansas State University, KS, USA.)

after the establishment of up to 20 years, or more. *M. × giganteus* has a high carbon sequestration capacity as well because of its dense rhizome and root system (Chung & Kim, 2012). Commonly, the initial planting density per ha is between 10,000 and 13,000 plants. The main characteristics of Miscanthus as a prospective biofuel crop are as follows: exceptional cultivation adaptation in different climatic and pedological conditions, possibility to grow in soils of inferior quality, high dry matter yields, high energy value, exceptional resistance to diseases and pests, and low demand for nutrients. As a natural sterile hybrid, invasive spread is much lower in comparison with some other energy crops (Bilandžija, 2014).

2.5 *M. × giganteus* as an Effective Phytoagent

Plants have to meet certain requirements for application in phytoremediation of contaminated sites: to be resistant to pests, plant diseases, and contaminants

of different origin; to be able to grow at the same site long term. *M. × giganteus* has all of these properties (Clifton-Brown et al., 2008; Dauber et al., 2010). The plant is among the more promising bioenergy crops due to high yield, water and nutrient use efficiency, and lignocellulose content. Lewandowski et al. (2016) pointed that *M. × giganteus* has only weak ability to absorb contaminants; therefore, it can be cultivated in contaminated soils while obtaining relatively clean biomass.

The selection of *Miscanthus* for phytomanagement of different contaminated areas with simultaneous production of alternative energy source is getting popular (Amougou et al., 2011; Dubis et al., 2019; Kołodziej et al., 2016; Kvak et al., 2018; Lewandowski et al., 2005; Matyka & Kuś, 2016; Roik et al., 2019; Tryboi, 2018). Thus, because *Miscanthus* covers 15% of the total bioenergy plant market in some Eastern European countries (Geletukha et al., 2016), can stabilize and accumulate some trace elements, absorb and degrade contaminants of organic origin, facilitate carbon deposition, and improve physico-chemical properties of soil, this plant may be successfully applied for restoration of postmining (Kharytonov et al., 2019; Nurzhanova et al., 2019; Pidlisnyuk et al., 2020a, b) and postmilitary (Alasmary, 2020; Pidlisnyuk et al., 2018, 2019) sites (Table 2.7). *Miscanthus* brings ecological benefits with economic profit due to using biomass for energy and bioproducts.

2.5.1 *Miscanthus* Tolerance to Metals and Removal Capacity

Miscanthus' ability to grow in soils contaminated by trace elements (Alasmary, 2020; Pidlisnyuk et al., 2019; Wilkins, 1997) is determined by the following factors (Wang et al., 2020):

TABLE 2.7

Phytoremediation Potential of *M. × giganteus* to Different Trace Elements

Trace Element	Phytoremediation Potential	Reference
Cd	Rhizoextraction	Arduini et al. (2006)
	Excluder	Fernando and Oliveira (2004)
	Phytostabilization	Nsanganwimana et al. (2015)
Cr	Rhizoextraction	Arduini et al. (2006)
	Excluder	Fernando and Oliveira (2004)
Cu	Excluder	Fernando and Oliveira (2004)
Hg	Excluder	Fernando and Oliveira (2004)
Ni	Excluder	Fernando and Oliveira (2004)
Pb	Excluder	Pavel et al. (2014)
	Excluder	Fernando and Oliveira (2004)
	Phytostabilization	Nsanganwimana et al. (2015)
Zn	Accumulator	Pogrzeba et al. (2013)
	Excluder	Fernando and Oliveira (2004)
	Phytostabilization	Nsanganwimana et al. (2015)

- a. *Miscanthus* root systems are large and well-developed, and plant metabolism is vigorous. Also, carbon-containing compounds released by plant roots supply the microorganisms located in rhizosphere (Rhizobacteria) with nutrients and organic acids (Hromádko et al., 2014; Zgorelec et al., 2020). Such acids can suppress trace element toxicity. Guo et al. (2017) reported that under Cd stress *M. sacchariflorus* roots secreted malate which mitigated Cd toxicity for the plant, by reducing its absorption.
- b. Antioxidant and photosynthetic activities of *Miscanthus* are well developed. The antioxidant defense system plays a crucial role in plant stress response. Along with the ability to mitigate stress-induced disturbances, it can serve as an indicator of trace element toxicity-induced stress. An increase of malondialdehyde content reflects Cr stress (Jiang et al., 2018). Significant increases in chlorophyll content, superoxide dismutase, and peroxidase activities are observed in *M. floridulus* and *M. sacchariflorus* growing in soil slightly contaminated by Pb, Zn, or Cd (Zhang et al., 2015). *M. x giganteus* behavior was similar under Pb and Zn stresses (Nurzhanova et al., 2019).
- c. The *Miscanthus* rhizosphere contains many microbial colonies that participate in plant–soil interaction (Wang et al., 2020). Schmidt et al. (2018) reported that plant inoculation with bacteria and fungi isolated from different *Miscanthus* species' rhizospheres improved plant growth. Firmin et al. (2015) obtained the same result after inoculating *M. x giganteus* by *Funneliformis mosseae*. Inoculation of *Miscanthus* rhizomes with plant growth promoting bacteria increased the biomass by ~77% after first vegetation season in postmining soil contaminated by trace elements (Pidlisnyuk et al., 2020a; Pranaw et al., 2020).

2.5.2 Changes in Soil Parameters Induced by *Miscanthus* Phytoremediation

Miscanthus planting in contaminated soils can increase soil carbon content, enhance aggregate stability, and improve water-holding capacity. The improving effect of the plant on soil physiochemical properties is mainly attributed to decomposition of underground organs and litter of root residuals in soil (Wang et al., 2020). McCalmont et al. (2015) showed that the decomposition of litter and underground organs of *Miscanthus* provides a large amount of organic carbon to soil, which increases soil organic matter, promotes soil nutrient cycling, improves the texture, structure, and water-holding soil capacity, and reduces soil nutrient loss.

Miscanthus was cultivated in marginal soil with the application of soil amendments, biochar, and biosolid, that enhanced the abundance of humus and mycorrhizal fungi, and improved soil fertility and hydraulic properties. Biosolids exerted the most pronounced effect (Allami et al., 2019).

Zhang et al. (2020) applied mixed planting of *Miscanthus*, Masson pine, and Bamboo for phytoremediation of a mining area. After 3 years of cultivation, the abundance of the mixed vegetation was tremendously higher, and microflora in remediated soil was larger in comparison with the control one. *Miscanthus* significantly reduces the release of NO_x and increases the absorbing capacity for CH_4 . The net release of greenhouse gases was reduced to an extent of 4.08 t CO_2 -eq per hectare per year (Mi et al., 2018).

In the long run during *Miscanthus* cultivation, soil carbon sequestration could be significantly different (Holder et al., 2019). During one life cycle (15 years), *Miscanthus* may release twice the amount of greenhouse gas in comparison to permanent grassland. Compared to the grassland soils, the surface soils of *Miscanthus* fields tend to have a risk of acidification due to higher concentrations of P and K (Hu et al., 2018). Therefore, when evaluating the impacts of *Miscanthus* cultivation, soil characteristics and soil organic carbon stability should be taken into consideration in the long-term perspective.

2.6 *Miscanthus* Phytotechnology in Action

2.6.1 *M. × giganteus* Application for Phytoremediation of Trace Elements' Contaminated Mining Soil, Tekeli, Kazakhstan

The research soil was sampled around the Tekeli Mining and Processing Complex of "Kazzinc", Kazakhstan. Soil was contaminated by trace elements in concentrations that exceeded the maximum permissible levels in Kazakhstan, i.e., the exceeding for Pb was in 29 times, As – 5 times, Zn – 11 times, Sr – 22 times, Cu – 13 times. Research soil belonged to saline and sandy types; its pH (water) ranged from 8.3 to 9.9 (Nurzhanova et al., 2019).

The experiment lasted two vegetation seasons. During the experiment soil and *M. × giganteus* tissues (root, stems, and leaves) were analyzed for the content of eleven trace elements: As, Pb, Zn, Co, Ni, Cr, Cu, Sr, Mn, V, and U. These elements mainly accumulated in the *M. × giganteus* root system. Accumulation of Zn, Sr, and Mn was higher than others (Figure 2.8). *M. × giganteus* behaved as an excluder (BCF and TLF values are lower than 1) preferentially accumulating the observed trace elements in roots; however, in relation to Mn, Sr, and Zn the plant acted as extractor (BCF < 1 and TLF ≥ 1) (Nurzhanova et al., 2019).

2.6.2 *M. × giganteus* Application for Phytoremediation of Post-Industrial Soil Contaminated with Trace Elements, Bakar, Croatia

This experiment was based on monitoring of *M. × giganteus* phytoremediation potential in relation to post-industrial soil of Rijeka-Bakar industrial zone, Croatia, which was contaminated by different trace elements (Pidlisnyuk et al., 2020b). The biomass parameters and concentrations of Ti, Mn, Fe, Cu,

FIGURE 2.8

Element accumulations in *M. × giganteus* tissues during two vegetation seasons

Zn, As, Sr, and Mo in stems, leaves, and roots were analyzed in each of three vegetation seasons at harvest. The following categories were used as features affecting the phytoremediation process: the difference in trace elements distribution along the plant; trace element concentrations in the researched soil; different regimes of trace elements absorption by roots and transmigration to plant organs; and vegetation season. Results of the statistical analysis (Pidlisnyuk et al., 2020b) showed that the main factor was trace element organ distribution which was essential for Ti, Fe, and Cu. The difference in trace element concentration in soil significantly correlated with Zn and Mo was essentially lower with As, Sr, and Mn, while for Ti and Cu correlation was not detected. The impact of the combined effect of two factors (trace elements organ distribution and difference in trace element concentration in soil) was detected for two elements: more prominent for Cu and smaller for Ti.

The plants organs (variable “Zone”) mainly affect the trace elements concentration variations, i.e., accumulation in specific plants part: it was the most essential for Ti, Fe, and Cu and the smallest for Mn. The second factor (trace elements concentration in soil – variable “Experiment”) was the most essential for Zn and Mo; however, much less for As, Sr, and Mn; limited for Fe; and was not observed for Ti and Cu. The combined effect of the above two factors was detected for two elements: higher for Cu and lower for Ti (Figure 2.9).

2.6.3 Field Study Results, Fort Riley, Kansas, USA

In a field study established in 2016, on an US Army reservation in Fort Riley, KS, *Miscanthus* was planted in an area with soil total Pb concentration ranging from 900 to 1500 mg kg⁻¹ and near-neutral soil pH. Five treatments were evaluated: (i) control without tillage with existing vegetation; (ii) no-tillage, no additional amendments planted with *Miscanthus*; (iii) tilled soil, no additional amendments planted with *Miscanthus*; (iv) tilled soil amended with triple

FIGURE 2.9

The components of the element concentration variation (after Box-Cox transformation) depended on plant organs (variable 1 – “Zone”), experiment treatment (variable 2 – “Experiment”), and its interaction (1*2) (with vegetation duration as a covariate). Notes: Zone – the effect of the plant organs (roots, leaves, stems), experiment – the effect of the experiment treatments (level 1–5), 1*2 – the interaction effects of the Zone and Experiment.

superphosphate (at 5:3 Pb:P molar ratio) planted with *Miscanthus*; and (v) tilled soil amended with organic P source (class B biosolids applied at 45 Mg ha⁻¹ air-dry weight basis) planted with *Miscanthus*. Results from 2016 to 2018 showed that one-time addition of soil amendments to Pb-contaminated soil supports establishing and stabilizing *Miscanthus*, increasing biomass yield as well as reducing phytoavailability and bioaccessibility of Pb (as measured by physiological-based extraction test procedure developed by Ruby et al. (1996) and modified by Medlin (1997)). Moreover, biosolids-treated plots showed improved soil enzyme activities, organic carbon, and microbial biomass (Alasmay et al., 2020). X-ray absorption spectroscopy results indicated pyromorphite, Pb associated with Fe minerals, and Pb adsorbed to humic acid were the dominant Pb species in P-amended and nonamended soils (Unpublished data, Alasmay and Hettiarachchi). The results suggest that *Miscanthus* can be grown successfully in Pb-contaminated military site soils combined with soil amendments, while minimizing the associated environmental risks.

2.7 Conclusions

Using energy crops in phytostabilization of soils contaminated with trace elements is one of the green technologies that provides ecological, economic, and social solutions for contaminated areas, while meeting energy needs and

mitigating climate change. The classification of plant species into corresponding groups (hyperaccumulator, accumulator, indicator, excluder) is complex as different conditions (soil type, pH, climate, location, media, plant properties, choice of cultivars, etc.) can influence plant uptake of trace elements and there is no universal approach. *Miscanthus* proved its ability to grow and to remediate soils contaminated by trace elements with sufficient biomass yield. Besides the obvious advantages of *Miscanthus* as a phytoremediation agent, its cultivation on the marginal and slightly contaminated lands can improve the soil biological parameters, such as basal respiration, microbial biomass carbon, fluorescein diacetate hydrolytic activity, other enzymatic activities, and simultaneously prevent soil and water erosion. The application of *Miscanthus* in phytomanagement can improve soil health and help to supply biomass for utilization to obtain energy or bioproducts. Utilization of *Miscanthus* for phytomanagement of differently contaminated soils is a prospective green technology with potential widespread commercial feedback.

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