- Soil-plant-microbial interactions engender unique processes influencing the overall plant metabolism as well as transformations of xenobiotics.
- Highly developed root systems allow plants to control large areas of soil at different depths and create micro-conditions convenient for the multiplication of microorganisms in their rhizosphere with the help of exudates.
- The large surfaces of plant leaves permit the absorption of pollutants from the air via the cuticle (lipophilic compounds) and stomata (gases).
- A well-developed internal transportation system for nutrients works in both directions and allows environmental contaminants to be distributed throughout the entire plant.
- Plant-microbial interaction creates a microenvironment resulting in the concentration and penetration of contaminants at and into the roots.
- The autonomous synthesis of vitally important organic compounds by photosynthesis requires primary ammonia (via uptake of nitrate or ammonia from the soil, or in the case of leguminous plants as a result of symbiotic nitrogen fixation). This process is important since remediation of polluted sites requires additional metabolic force especially in the case of prolonged contact with contaminants.
- Plants contain the apparatus required for the full set of biochemical and physiological processes of detoxification, and have no need for additional non-plant microorganism-based technological help.

One should moreover note:

- The existence of constitutive and inducible enzymes catalyzing degradation, conjugation and other detoxification processes.
- The availability of a large intracellular space to deposit the residues of toxic compounds as conjugates, and to accumulate heavy metals.
- The functionalization or further transformation of organic contaminants in plant cells (conjugation, deep oxidation etc.), depending on the molecular structure of the contaminant.

These characteristics confer advantages distinguishing higher plants from other organisms and determining their universal ability to absorb the great majority of contaminants from soil, water and air. To evaluate the ecological potential of higher plants one should keep in mind that in spite of global urbanization plants still occupy more than 40% of the land.

The main disadvantage of plant-based cleaning technologies is their strong dependence on climate. Climate is a very important factor for growth, development and metabolic activity of plants; climate is the main limiting factor in the distribution and survival of plants. The decrease of plant detoxification activity is especially noticeable in areas remote from the equator. According to their tolerance of temperature, plants are divided into the following groups: equatorial, tropical, subtropical, Mediterranean, warm-temperate, cool-temperate, boreal, and polar [521]. For instance, equatorial evergreen tropical rainforest plants permanently maintain ecological activity regardless of the season. Other plants, even subtropical ones, are influenced by the seasons. Boreal and treeless tundra vegetation types with a short or very short summer and a long and cold winter are less effective for environment decontamination. All above-mentioned plant groups have been well characterized according to their ecological importance [292]. Microclimate, determined by zonal and regional factors, is an important parameter for the cultivation of plants. The zonal climate is the result of the energy balance prevailing at different latitudes. Regional climate depends on the distance from seas, oceans, ocean currents (warm: e.g., Gulf Stream, Kuroshio; cold e.g., Labrador, Benguela), and such factors as prevailing winds (and position with respect to mountain barriers, e.g. leeward), etc. Climate and weather are continuously changing albeit at different time scales. The interaction of meteorological factors, such as air temperature, humidity, wind speed and direction, and precipitation (its quality and nature) with each other, determines the frequency of fluctuations in weather, which, in turn, significantly affects plant detoxification abilities.

The activity of the rhizospheric microflora also depends on temperature. Temperature determines the substrate exchange intensity between soil, plant root systems and microbial consortia [292]. As a result of contacts between these compartments, the root system takes up inorganic compounds dissolved in water and nutrients and releases exudates (enzymes, carbohydrates, vitamins, organic acids, growth factors, etc.). The exudates in the soil create a favorable environment for the development of microorganisms of different taxonomic groups (bacteria, actinomycetes, fungi). The development of soil microorganisms and their intimate contact with root systems leads to the activation of potential metabolic interactions between roots and microorganisms. The mucus covering of the root caps provides an additional substrate for soil microflora. The profit for plants in this environment is the acceleration of exchange processes and the increased velocity of nutrient uptake and transportation, including organic substrates and heavy metals.

A high potential to carry out biochemical reactions, and an increased absorption surface developed in the root systems, allow mycorrhizal fungi to participate in nutrient uptake [292]. The worldwide distribution of these fungi indicates their supreme importance in plant-microbial interactions. These fungi belong to the subclass of lower fungi – Zygomycetes. Most plants are hosts of mycorrhizal fungi. Interaction of these fungi with plants is highly mutually desirable. Plants provide the fungi with carbohydrates and receive back chemical elements and organic compounds required for the plants' growth and activation of root metabolic processes.

The plant cell is not a small factory permanently able to absorb and metabolize organic contaminants of different structures. Oxidative or any other kind of xenobiotic degradation (reduction, hydrolysis) requires extra energy, which a plant cell has to provide. There are intracellular processes in plants that undergo deviations from the norm as a result of the penetration of xenobiotics into plant cells. Plant cell ultrastructure is sensitive to the action of contaminants, and according to the changes engendered by them, their intracellular concentrations can be classified as metabolizable or lethal [544]. The transformation of contaminants is closely related to the metabolic activity of a plant cell. The present authors have shown (hitherto unpublished data) that small doses of contaminants with aliphatic and aromatic structures induce the activation of key Krebs cycle enzymes such as malate dehydrogenase and enzymes providing the plant cell with nitrogen-containing organic compounds, including catabolic fuel in the case of energy deficiency (glutamine synthetase, glutamate dehydrogenase) [288]. The extra energy required by detoxification processes is partially spent on the induced synthesis of the enzymes participating in xenobiotic degradation, their movement and deposition, e.g. in vacuoles. Detoxification processes are connected to photosynthesis, the intensity of which is significantly decreased under the influence of contaminants [182, 454]. Xenobiotic transformations are closely related to the majority of intracellular metabolic processes requiring extra energy, and this energy dependence is one of the main limiting factors in the detoxification potential of plants.

A plant's ecological potential is directed to remove contaminants from the environment. The purposeful application of plants can be of long-term or of short-term advantage, depending on the targeted goal. For phytoremediation, long-term application of the planted system to exploit and amortize its potential and maintain its continued effectiveness is recommended. Monitoring should follow short-term cleanup. Essentials of monitoring whose results are used for plant selection include the following: type and concentration of constituent elements; frequency and duration; sampling methods; locations; and quality control requirements [152]. Sometimes, a phytoremediation process would take too much time and, hence, would not be acceptable. All phytoremediation technologies depend on the growth rates of the plants, which are characterized by seasonal activity; growth rate often limit the application efficiency. Several growing seasons may be needed to attain the effective age of the plant for optimal phytoremediation.

4.1 Plants for phytoremediation

The realization of phytoremediation technologies implies the planting of a contaminated area with one or more specific, previously selected plant species with the potential to extract contaminants from the soil. The treatment continues by harvesting the plants, composting, disposal in a landfill, or incinerating them. To create a truly effective phytoremediation system all components of the system should be thoroughly analysed. The major constitutive component of such a system is obviously the plant itself. The goal of plant selection is to choose a plant species with appropriate characteristics.[1] A survey of the vegetation on site should be undertaken to determine what species of plants would have the best growth at the contaminated site, taking into account the abilities of the plants to accumulate and degrade the contaminants.

The assessment of the detoxification potential of the plant is determined by the rate and depth of contaminant uptake from the soil, accumulation in the plant cell, and the degree of contaminant transformation to regular cell metabolites. The best plants for a particular phytoremediation task should be selected based on multiple plant characteristics. First, the actual phytoremediation–related characteristics of the candidate plants should be established, notably:

- Overall ability to take up and degrade contaminants in the soil or groundwater.
- Ability to accumulate organic and inorganic contaminants in their cells and intracellular spaces.
- Excretion of exudates to stimulate the multiplication of soil microorganisms and secretion of enzymes participating in the initial transformations of the contaminants.
- Existence within the cells of contaminant-degrading or conjugating enzymes (oxidases, reductases, transferases, esterases, etc.).

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[1] At present, very little work has been done on increasing the effectiveness of the phytoremediation system by creating biocoenoses, or communities, in which the plants act synergistically. In other words, at present the focus is on single contaminants, and the goal of selection is to find specific plant species for their elimination. A considerable body of knowledge, acquired from laboratory and field experiments, exist for identification of the optimal candidate. On the other hand, where several contaminants need to be eliminated, a corresponding mixture of the individually optimum candidates may not constitute the best solution. To date, only some types of synergisms between plants and microorganisms have been investigated.

- High resistance against contaminants, i.e., that the plants' growth and metabolism is not adversely affected by the contaminants.
- The root system (main and fibrous); the range of rooting depth of the plants.
- Whether the plants are endemic and non-agricultural.
- Tolerance to salty soil (halophilicity).
- Appropriate adaptation to warm or cold conditions.
- Growth rate.

It is assumed that the nature and level of the contaminants have already been determined. It is also important to establish the localization and distribution of toxic compounds (area and depth of contamination). Important environmental factors bearing on the selection of the best remediation technology are: soil type and characteristic parameters (pH, average humidity, salt content, metal concentration), the presence of parasites, and the expected amount of precipitation during the duration of the remediation process.

Table 4.1 below presents plants widely used in phytoremediation.

It is generally true that the planting of almost any kind of vegetation, including agricultural flora, is beneficial for the human environment. However, in order to make the most of the ecological potential of each particular plant, the selection should be carried out according to the listed criteria. Undoubtedly, technologically the most important part of the plants is the root system, which takes up contaminants from the soil and performs the initial stages of their transformation or accumulation within it. Therefore it is clear that the type of roots and their depth, distribution and type, and degree of ramification are extremely significant components for the successful realization of any phytoremediation technology. A so-called fibrous root system has numerous fine roots providing maximum contact with soil due to the high surface area of the roots. The rooting depth of plants greatly differs between individuals and species (Table 4.2).

Some plants are able to accumulate metals, but the low growth rates typical of these plants limit the total biomass and indicate that the total mass of accumulated metals will be low. Better extraction of toxic compounds from soil may be achieved by the use of mixed plant cultures, but at present there are very little data on their effectiveness.

Table 4.1. Promising plant species for the remediation of sites polluted by organic contaminants

Organic contaminant	Plant Species	Comments	Refs
1	**2**	**3**	**4**
Aromatic hydrocarbons (benzene, toluene)	Maple (*Acer campestre*) Oleaster (*Elaeagnus angustifolia*) Locust (*Robinia pseudoacacia*) Caucasian pear (*Pyrus caucasica*) Walnut *(Juglans regia)* Almond (*Prunus amygdalus*) Cherry (*Cerasus avium*) Cherry (*Cerasus vulgaris*) Amorpha (*Amorpha fructicosa*) Chestnut (*Castanea sativa*) Apple (*Malus domestica*) Zelkova (*Zelkova caprinifolia*) Poplar (*Populus canadensis*) Ryegrass (*Lolium perenne*) Lilac (*Syringa vulgaris*) Weeping willow (*Salix*) Catalpa (*Catalpa bignonioides*) Oriental plane (*Platanus orientalis*) Sophora (*Sophora japonica*)	Plants capable of absorbing 1-10 mg of benzene and toluene per kg fresh leaves per day from air	[127, 510, 515]
	Alfalfa (*Medicago sativa* L.)	Can remove benzene from soil	[165]
		Can enhance biodegradation of toluene by associated microorganisms	[101]

Table 4.1. (cont.)

1	2	3	4
Gaseous alkanes (methane, ethane, propane, butane)	Tea (*Thea sinensis*) Vine (*Vitis vinifera*) Poplar (*Populus canadensis*) Walnut (*Juglans regia)* Maple (*Acer campestre*) Ryegrass (*Lolium multiflorum*) Maize (*Zea mays)* Kidney bean (*Phaseolus vulgaris*)	Plants capable of absorbing 0.1-10 mg of gaseous alkanes per kg fresh leaves per day from air	[508]
Petroleum hydrocarbons (PHC)	Pine (*Pinus sylvestris* L.)	Plant roots enhance rhizospheric degradation of PHC in soil	[227]
	Alfalfa (*Medicago sativa* L.)	Can remediate crude oil-contaminated soil	[535]
	Spartina alterniflora (salt marsh sp.) *Juncus roemerianus* (salt marsh sp.) *Spartina patens* (brackish marsh sp.) *Sagittaria lancifolia* (fresh marsh sp.) Clover *(Trifolium* sp.*)*	Can remediate oil spills in marshes	[311]
	Tall fescue (*Festuca arundinacea* Schreber) Bermuda grass *(Cynodon dactylon)* Ryegrass (*Lolium multiflorum*)		[446]
	Ryegrass (*Lolium perenne*)	Can remediate PHC-contaminated soil and dredged material	[33, 237]

Table 4.1. (cont.)

1	2	3	4
PAHs	Ryegrass (*Lolium multiflorum*) Hybrid poplar (*Populus* sp.) Clover (*Trifolium* sp.)		[488]
	Sorghum (*Sorghum bicolor*) Switch grass (*Panicum virgatum*)	Enhance rhizospheric degradation of PAHs in soil	[401]
	Big bluestem (*Andropogon gerardii*) Little bluestem (*Schizachyrium scoparius*) Indian grass (*Sorghastrum nutans*) Switch-grass (*Panicum virgatum*) Canadian wild rye (*Elymus canadensis*) Western wheatgrass (*Agropyron smithii*) Side oats grama (*Bouteloua curtipendula*) Blue grama (*Bouteloua gracilis*)	A mixture of prairie grasses that degrade PAHs	[13]
	Tall fescue (*Festuca arundinacea* Schreber) Alfalfa (*Medicago sativa* L.)	Plants capable of absorbing and degrading naphthalene	[446]
	Prairie buffalo grass (*Buchloe dactyloides*) Kleingrass (*Panicum coloratum* var. 'Verde')	Can decrease naphthalene content in clay soil	[392]
Nitrobenzene	Soybean (*Glycine max* L. Merr. cv. Fiskby v)		[170]
Phenols	Soybean (*Glycine max* L. Merr. cv. Fiskby v)		
	Cane (*Scirpus lacustris* L.)		[449]

Table 4.1. (cont.)

1	2	3	4
Phenols (cont.)	Alfalfa (*Medicago sativa* L.)	Can enhance degradation of phenol by associated microorganisms	[165]
	Potato (*Solanum tuberosum*) White radish (*Raphanus sativus*) Horseradish (*Armoracia rusticana* P. Gaerter, Meyer & Schreb)	Plants with a highly active peroxidase that oxidizes phenols (used in waste-water treatment)	[104]
Polychlorinated solvents	Hybrid poplar (*Populus trichocarpa x P. deltoides*), Aspen (*Populus* sp.) Cottonwood (*Populus* sp.)	Poplars that transpire, metabolize or mineralize 98% of TCE in soil at a concentration of 260 mg per kg	[264]
	Soil green alga (*Chlamydomonas reinhardtii*) Marine green alga (*Dunaliella tertiolecta*)	Algae capable of absorbing and de-grading TCE at a concentration of 500 mg per kg soil	[124]
Trichloroethene (TCE) Tetrachloroethane	Wild carrot (*Daucus carota*) Spinach (*Spinacia oleracea*) Tomato (*Lycopersicon esculentum*)	Plants able to absorb and transform TCE from groundwater	[436]
	Waterweed (*Eichhornia crassipes*)		[415]
	Black locust (*Robinia pseudoacacia*)	Can volatilize TCE from groundwater	[355]
	Hybrid poplar (*Populus* sp.)		[61]
	Alfalfa (*Medicago sativa*)	Plant exudates promote degradation of TCE in its rhizosphere	[352]

Table 4.1. (cont.)

1	2	3	4
Polychlorinated solvent (cont.) Dibromoethane TCE	Lespedeza (*Lespedeza cuneata* (Dumont)) Loblolly pine (*Pinus taeda* L.) Soybean (*Glycine max* L. Merr. cv. Davis)	Plants able to increase mineralization of TCE in soil	[7]
	Koa haole (*Leucaena leucocephala* var. K636)	A tropical leguminous tree	[122]
PCBs	Red mulberry (*Morus rubra* L.) Crabapple (*Malus fusca* (Raf.) Schneid) Osage orange (*Maclura pomifera* (Raf.) Schneid)	Plants that produce exudates that stimulate growth of PCB-degrading bacteria	[169]
	Spearmint (*Mentha spicata)*	Plant that induces cometabolism of PCB in its rhizosphere	[191]
	Barley (*Hordeum vulgare* L. cv.Klages)		[333]
Aroclor 1260	Tall fescue (*Festuca arundinacea* Schreb.) Alfalfa (*Medicago sativa* L.) Flatpea (*Lathyrus sylvestris* L.) Lespedeza (*Lespedeza cuneata* Dum) Deertongue (*Panicum clandestinum* L.)	Can enhance mineralization in soil microcosm; decreased levels from 100 to 23-33 mg PCB kg^{-1} soil in 4 months	[154]
Delor 103	Black nightshade (*Solanum nigrum* L.)	Plant effecting 40% mineralization of 100 mg PCB per kg soil in 30 days	[324]
Chlorinated benzoic acid	Slender wheatgrass (*Agropyron pinnata)* Western wheatgrass (*Agropyron smithii)*	Prairie grass species	[463, 500]

Table 4.1. (cont.)

1	2	3	4
Pesticides Simazine	Parrot feather (*Myriophyllum aquaticum* (Vell.) Verdc.) Canna (*Canna* x *hybrida* L. 'Yellow King Humbert)		[272]
Atrazine	Hybrid poplar (*Populus deltoides x nigra* DN34 Imperial Carolina)		[61]
	Kochia *(Kochia scoparia* L.Schrad*)*	Can enhance rhizospheric mineralization of atrazine in soil	[374]
	Pine (*Pinus ponderosa*)	Can support degradation by ectomycorrhizal fungus *Hebeloma crustuliniforme*	[187]
Chloroacetamides	Maize (*Zea mays* L.)		[231]
2,4-D, DDT	Hybrid poplar *(Populus sp.)*		[501]
Metolachlor with Atrazine	Coontail (*Ceratophyllum demersum*) Canadian pondweed (*Elodea canadensis*) Common duckweed (*Lemna minor*)	Aquatic plants that remediate herbicides in water	[403]
Hexachlorobenzene, entachlorobenzene, trichlorobenzene	Barley (*Hordeum vulgare* L. cv.Klages)		[333]

Table 4.1. (cont.

1	2	3	4
Chlorinated phenols (4-chlorophenol to pentachlorophenol)	Duckweed (*Lemna gibba*)	A floating plant that removes herbicides from water	[148]
Cyanazine with Fluometuron	Ryegrass (*Lolium multiforum* L.) Hairy vetch (*Vicia villosa* Roth) Rice (*Oryza sativa* L.)	Can enhance degradation of herbicides in soil via stimulation of rhizosphere bacterial populations	[520]
Atrazine, Metolachlor, Trifluralin	Kochia (*Kochia scoparia* L.Schrad) Knotweed (*Oiktgibyn* sp.) Crabgrass (*Digitaria* sp.)	Can enhance microbial degradation in rhizosphere, i.e., 45% of atrazine, 50% of metolachlor and 70% of trifluralin in 14 days	[8]
Pentachlorophenol (PCP), Parathion, Diazinon	Wheat grass (*Agropyron cristatum*)	Plant roots enhance rhizospheric degradation of PCP in soil	[164]
	Hard fescue (*Festuca ovina* var. *duriuscula*) Tall fescue (*Festuca arundinacea*) Red fescue (*Festuca rubra*)	A mixture of fescues with high germination rates and high biomass formation in PCP- and PAH-contaminated soil	[385]
	Waterweed (*Eichhornia crassipes*)		[415]
	Crested wheatgrass (*Agropyron desertorum* Fischer ex Link Schultes)	Enhances mineralization of PCP from 100 to 23.1 mg per kg soil in 20 weeks	[164]
	Kidney bean (*Phaseolus vulgaris* cv. 'Tender Green')	Enhances rhizospheric degradation of herbicides	[241]

Table 4.1. (cont.)

1	**2**	**3**	**4**
Bentazon	Black Willow (*Salix alba*) Bald cypress (*Taxodium distichum*) River bitch (*Betula nigra*) Cherry-bark oak (*Quercus falcata*) Live oak (*Quercus virginiana*)	These plants have a high capacity to degrade bentazon	[91]
Aldrin, Dieldrin	Arctic hairgrass (*Deschampsia bernigensis*) Felt-leaf willow (*Salix alaxensis*) Red fescue (*Festuca rubra*) Spikerush (*Eleocharis palustris*)		[532]
Explosives	Switch grass (*Panicum virgatum*)	Prairie grass species	[379]
	Spinach (*Spinacia oleracea*)		[335]
	Parrot feather (*Myriophyllum aquaticum*) Water milfoil (*Myriophyllum spicatum*)	Aquatic plants	[335, 369, 517]
2,4,6-Trinitrotoluene (TNT)	Stonewort (*Nitella* sp.)	Algae	
	Parrot feather (*Myriophyllum aquaticum*) Sweet-flag (*Acorus calamus* L.) Wool-grass (*Scirpus cyperinus* L. Kunth) Waterweed (*Elodea canadensis* Rich. in Michx) Sago pondweed (*Potamogeton pectinatus* L.) Water star-grass (*Heteranthera dubia* Jacq. MacM) Curlyleaf pondweed (*Potamogeton crispus* L.)	Emergent and submerged plant species with a high ability to remove TNT from water and recommended for phytoremediation of explosives-contaminated water around army ammunition plants	[31, 32]

Table 4.1. (cont.)

1	2	3	4
TNT (cont.)	Kidney bean (*Phaseolus vulgaris* cv. 'Tender Green')		[222]
	Hybrid poplar (*Populus* sp.)		[61, 222]
	Bromegrass (*Bromus erectus*)	A plant-microbial consortium with *Pseudomonas* sp.	[464]
	Soybean (*Glycine max*) Ryegrass (*Lolium multiflorum*) Pea (*Pisum sativum*) Chickpea (*Cicer arietinum*)	Plants that can absorb 0.15–0.20 mg TNT per gram fresh biomass per day	[268]
	Hybrid willow (*Salix* EW-13) Hybrid willow (*Salix* EW-20) Hybrid poplar (*Populus* ZP-007) Birch (*Betula pendula*) Norway spruce (*Picea abies*) Pine (*Pinus sylvestris*)	Five-year-old trees of these species are able to uptake TNT from contaminated soil: *Salix* EW-20, 8.5; *Salix* EW-13, 6.0; *Betula pendula,* 5.2; *Populus* ZP-007, 4.2; *Picea abies* – 1.9; *Pinus sylvestris,* 0.8 (g of TNT per m^2 soil per year)	[439]
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	Parrot feather (*Myriophyllum aquaticum* Vell. Verdc.) Sweet-flag (*Acorus calamus* L.) Wool grass (*Scirpus cyperinus* L. Kunth)		[31, 32]

Table 4.1. (continued)

1	2	3	4
RDX (cont.)	Waterweed (*Elodea canadensis* Rich. in Michx) Sago pondweed (*Potamogeton pectinatus* L.) Water star-grass (*Heteranthera dubia* Jacq. MacM) Curlyleaf pondweed (*Potamogeton crispus* L.)		[31, 32]
	Parrot feather (*Myriophyllum aquaticum*) Spinach (*Spinacia oleracea*) Indian mustard (*Brassica juncea)*		[335]
	Hybrid poplar (*Populus deltoides x nigra,* DN34)		[541]
	Kidney bean (*Phaseolus vulgaris*)		[222]
Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX)	Alfalfa (*Medicago sativa*) Kidney bean (*Phaseolus vulgaris*) Canola (*Brassica napa*) Wheat (*Triticum aestivum*) Ryegrass (*Lolium perenne*) Wild bergamot (*Monarda fistulosa*) Western wheatgrass (*Agropyron smithii*) Bromegrass (*Bromus sitchensis*) Koeleria (*Koeleria gracilis*) Goldenrod (*Solidago* sp.) Blueberry (*Vaccinium* sp.) Anemone (*Anemone* sp.) Common thistle (*Cirsium vulgare*) Wax-berry (*Symphoricarpos albus*) Western sage (*Artemisia gnaphalodes*) Drummond's milk vetch (*Astragalus drummondii*)	Terrestrial indigenous and crop plants able to absorb, translocate and accumulate HMX in foliar tissues (from contaminated soil from an anti-tank firing range)	[201]

Table 4.2. Rooting depth of plants used in phytoremediation technologies [151]

Plant	Root depth/m
Indian mustard	0.30
Grasses	0.60–1.20
Alfalfa	1.20–1.80
Poplar trees	4.50

Effective monitoring of the phytoremediation process requires the collection of extensive information, not in the least because many factors influence it apart from the plant species: availability of nutrients, daily maximum, minimum and average temperatures, illumination level (spectral characteristics and irradiance), humidity and its variation, etc. All these parameters should ideally be monitored.

Rapid formation of a large biomass, well-developed roots, and a strong defense system are the most important overall criteria for plants to be successfully applied to the phytoremediation of soils contaminated with heavy metals and organic contaminants.

Is it possible to improve the process of remediation carried out by plants by nongenetical interference? In this regard, encouraging results have been obtained by the application of bioactive preparations.[2] These preparations typically comprise a complex of amino acids and other nutrients including microelements, and are used for plant regeneration following damage due to unfavorable conditions in the surrounding environment, as well as for increasing yield, the development of above-ground biomass, promotion of the assimilation of minerals, facilitation of their transport with the plant sap stream, balancing metabolism, enhancing the plant defense system, metabolic regulation, and are boosters and stress relievers. Some of their characteristics are given in Table 4.3.

According to the authors' recent investigations, these bioactive preparations also increase plant resistance to the action of organic contaminants and heavy metals.

In plants exposed to TNT, benzene and 3,4-benzopyrene the addition of Fosnutren and Humiforte enabled the maintenance of chlorophyll content at the control level, the activation of enzymes participating in the oxidative degradation of pollutants: monooxygenase, peroxidase, phenoloxidase; and the activation of key metabolic enzymes: glutamine synthetase, glutamate

[2] For example those from Inagrosa Industrias Agrobiologicas S.A. (Spain) http://www.inagrosa.es/menu productos i.html.

and malate dehydrogenases, i.e. enzymes providing plant cells with nitrogen-containing compounds and energy. Fosnutren and Humiforte contributed to doubling the lead accumulation in roots of maize, kidney bean and yygrass. In shoots the effect of these bioactive preparations on heavy metal accumulation was not noticeable.

Table 4.3. Characteristics of some commercially available bioactive preparations

Product	Shelf life of product sealed in bottle/ years	Dosage of application (Min-Max)/ L ha^{-1}	Mean total quantity used per growth cycle/ L ha^{-1}	Effect and consequences
Aminol-forte	4	0.75–1.50	3-4	Increase in yield (20–30%). Reduction in pesticides and fertilizers needed (20–25%)
Fosnutren	6	0.75–1.50	3	Increase in yield (25–30%). Reduction of pesticides and fertilizers needed (20–25%)
Kadostim	5	0.75–1.50	3	Increase in carbohydrates, oils and protein content (30%). Reduction in pesticides and fertilizers needed (20–25%)
Humiforte	6	1.00–2.00	5	Increase in yield in horticulture (up to 50%), elimination of stress

Not all aspects of the action of bioactive preparations on the phytoremediation processes on differently polluted sites have been investigated yet, but it can be already stated that the preparations typically have a definitely positive effect on plant metabolic activity and promote increased resistance against the action of toxic compounds.

4.2 Phytoremediation technologies

Phytoremediation is a concept constructed from an emerging set of natural technologies to support clean-up strategies. This term is relatively new [397] and means plant-based action (*phyto* – plant, *remediation* – to recover). According to the most modern understanding of phytoremediation technologies, microorganisms also participate as important auxiliaries. Phytoremediation has received special attention in the last decade as an innovative, cost-effective and alternative combination of technological approaches. The main objective of scientists, agronomists, and engineers dealing with phytoremediation is to exploit by the most rational way possible the potential of this natural process. From the technological point of view phytoremediation is the use of vegetation to decontaminate soils and water from heavy metals and toxic organics. Very often, phytoremediation assumes the joint action of both plants and microorganisms.

The most effective technologies based on phytoremediation principles are targeted towards the gradual elimination from the soil of shallow contamination by organics, radionuclides and heavy metals. It is also important to underline that these *in situ* technologies do not damage soil structure and just slightly change soil microbial consortia, even when microorganisms of any taxonomic group (or groups) are introduced into the soil. When comparing the actions of plants and microorganisms on soil it should be noted that in the majority of cases their joint action directed towards xenobiotic degradation exceeds the arithmetical sum of the activity of each individually. At the same time some similarity exists between plants and microorganisms in assimilation of contaminants. After penetration into the cells of both types of organisms contaminants mainly undergo oxidative transformations. Microorganisms, due to their fast growing ability, much more easily regulated adaptation, fast inductive processes and their wide spectrum of enzymes participating in the degradation of organic xenobiotics, are much more active detoxifiers when expressing their activity per unit of dry biomass. A different situation is evident in the case of uptake of inorganics. Microorganisms are often able to accumulate high concentrations of heavy metals. After lysis (degradation) of the microbial cells their content, in spite of the metals, valency change, again becomes a constituent of the soil and hence no remediation takes place. Plants are also able to accumulate high amounts of heavy metals in their roots and subsequently transport them to organs above the ground, eliminating in this way contaminants from the soil.

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