Phytoremediation of heavy metals—Concepts and applications

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Uses of phytoremediation

Remediation of different <u>media</u>:

- air
- soils, sediments
- groundwater
- wastewater streams
  - industrial
  - agricultural
  - municipal, sewage

Uses of phytoremediation (cont.)

Remediation of different <u>pollutants</u>:

- inorganics:

- metals (Pb, Cd, Zn, Cr, Hg)
- metalloids (Se, As)
- "nutrients" (K, P, N, S)
- radionuclides (Cs, U)

- organics:

- PCBs
- PAHs
- TCE
- TNT
- MTBE
- pesticides
- petroleum hydrocarbons

Etc.

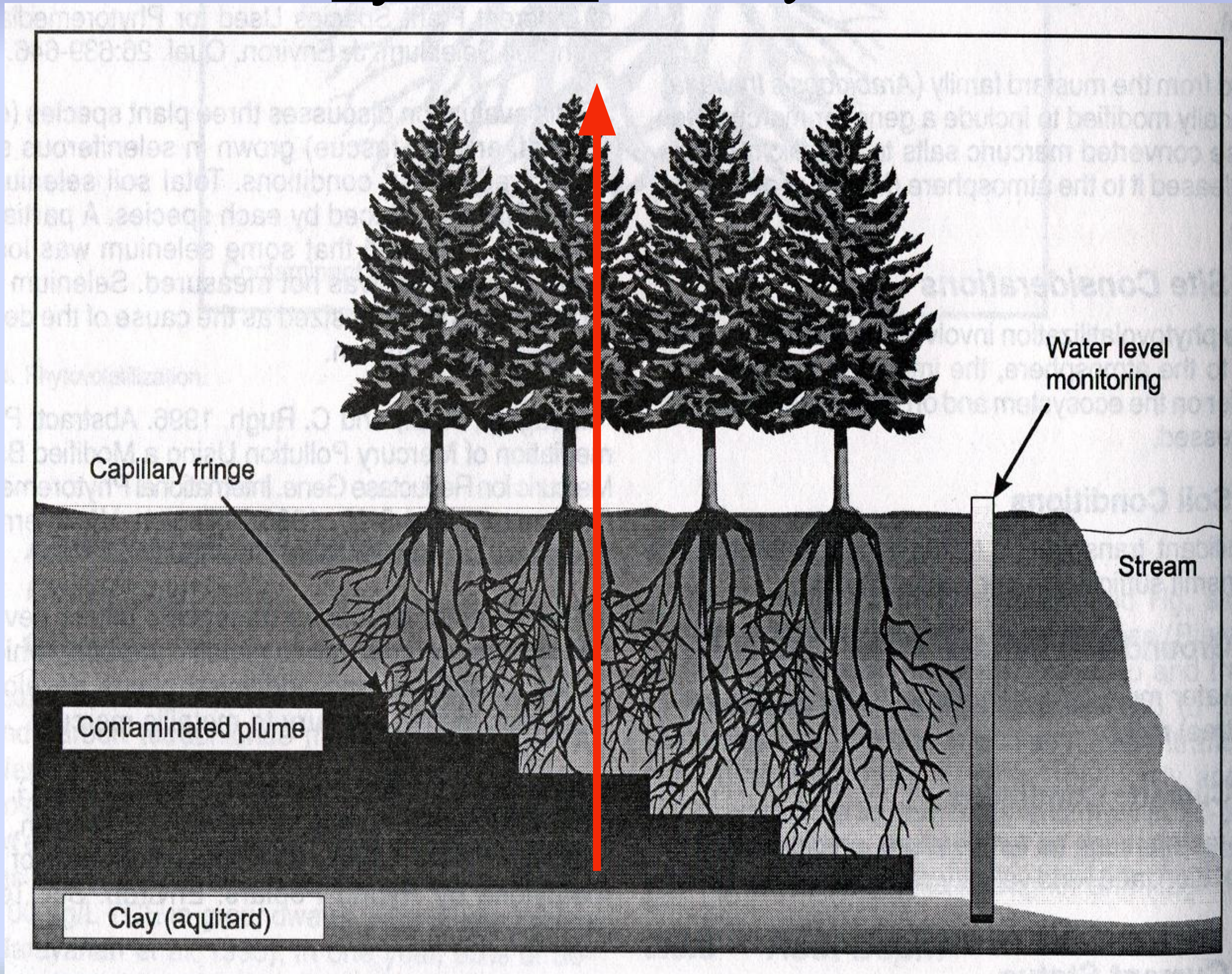
Uses of phytoremediation (cont.)

Remediation using different systems:

- farming polluted soil
- irrigation with polluted groundwater
- letting trees tap into groundwater
- letting plants filter water streams

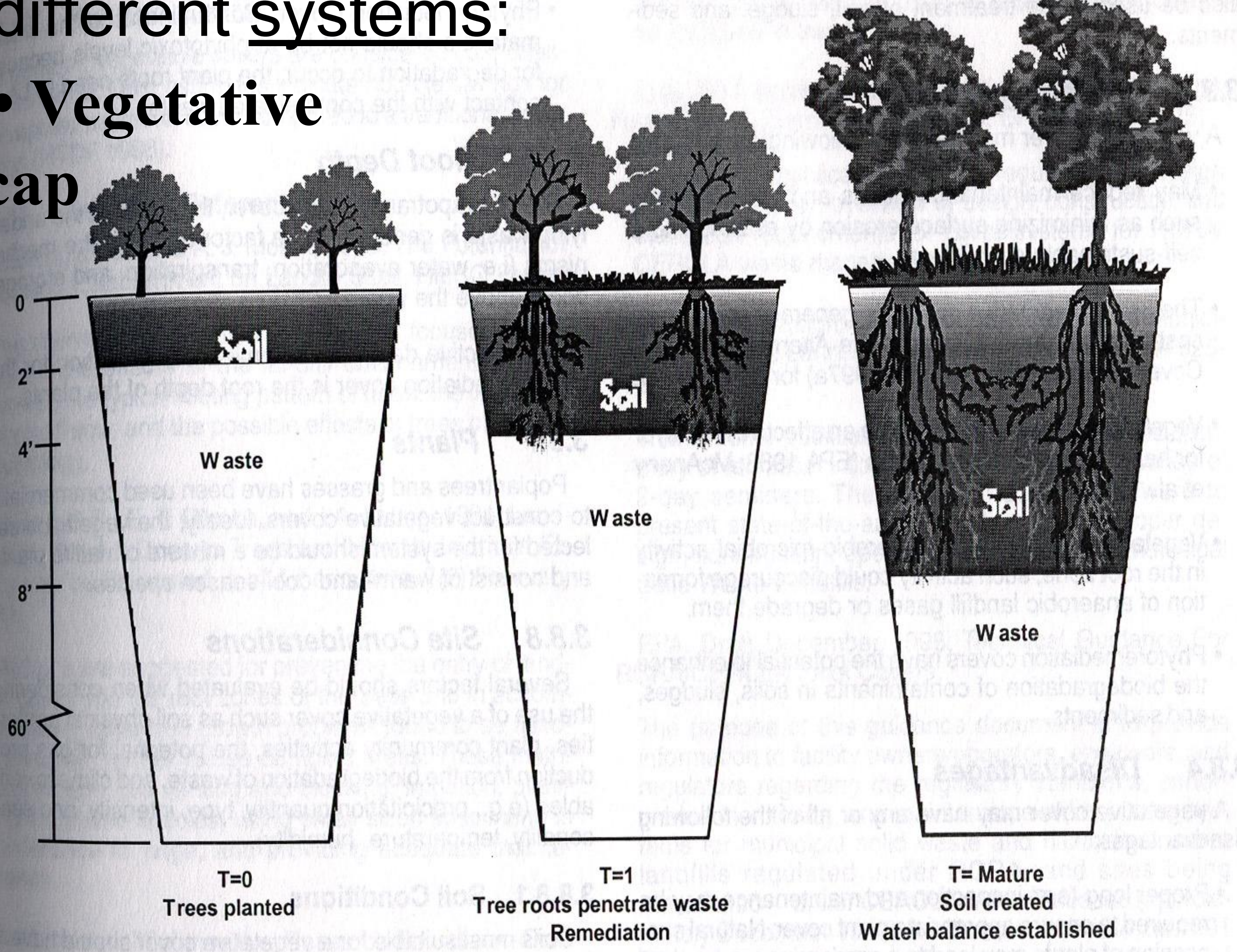
  constructed wetlands, hydroponics

different <u>systems</u>: Hydraulic barrier



different <u>systems</u>:

- **Vegetative cap**



different systems:

- Constructed wetlands


C
B
different systems:
hydroponics with polluted wastewater


Roots of mustard
Extend into effluent
Acting as filters for

Uses of phytoremediation (cont.)

Remediation using different plants

Properties of a good phytoremediator:

- high tolerance to the pollutants
- high biomass production, fast growth
- large, deep root system
- good accumulator/degrader of pollutant
- able to compete with other species
- economic value

Uses of phytoremediation (cont.)

Popular plants for phytoremediation

- trees

various organics
metals

poplar

gum tree

willow

Uses of phytoremediation (cont.)

Popular plants for phytoremediation (cont.):

Brassicaceae:

- For inorganics

Thlaspi

Alyssum

Brassica juncea

Uses of phytoremediation (cont.)

Popular plants for phytoremediation (cont.):

various grasses

for organics

buffalo grass

red fescue

hemp

for inorganics

kenaf

bamboo

Uses of phytoremediation (cont.)

Popular plants for phytoremediation

aquatic plants

cattail

parrot feather

salicornia

halophytes

for inorganics

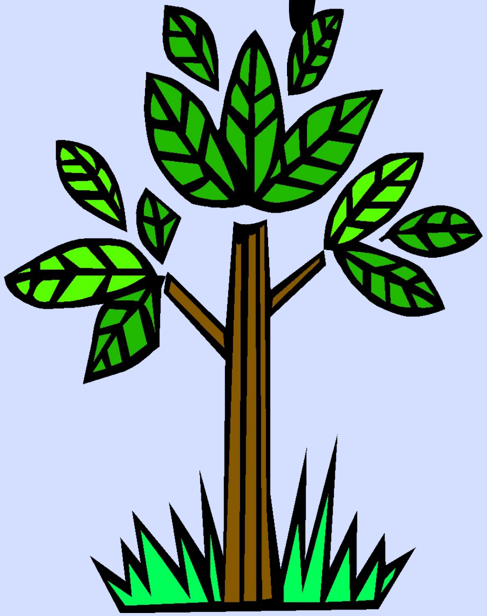
reed

spartina

for organics

poplar, willow

Advantages & Limitations of Phytoremediation



Phytoremediation

Solar energy

In situ

Fossil fuels for energy

Ex situ

Mechanical/chemical treatment

- Soil washing
- Excavation + reburial
- Chemical cleanup of soil/water
- Combustion

Phytoremediation vs. Mechanical/chemical treatment

Advantages of phytoremediation

- ~10 - 100x Cheaper

Excavation & reburial: up to $1 million/acre

Revegetation: ~$20,000/acre

Phytoremediation vs. Mechanical/chemical treatment

Advantages of phytoremediation (cont.)

- Less intrusive
- Can be more permanent solution
- Better public acceptance

Phytoremediation vs. Mechanical/chemical treatment (cont.)

Limitations of phytoremediation

- Can be slower

Limited by rate of biological processes

-Accumulation in plant tissue: slow

e.g. metals: average 15 yrs to clean up site

- Filter action by plants: fast (days)

- Metabolic breakdown (organics): fairly fast (< 1yr)

Phytoremediation vs. Mechanical/chemical treatment (cont.)

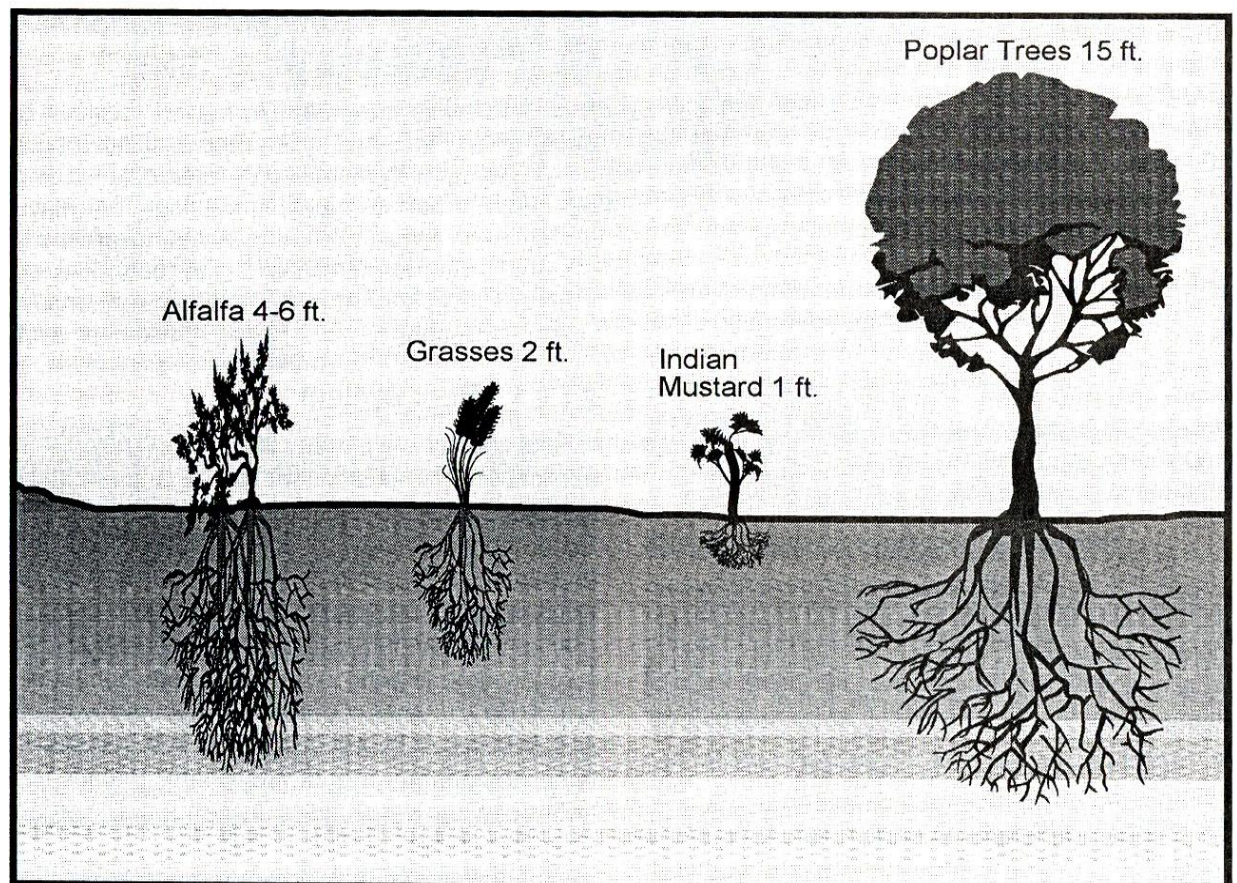
Limitations of phytoremediation (cont.)

- Limited root depth

Trees > prairie grasses > forbs, other grasses

Max depth ~5 m

Can be increased up to 20m with "deep planting"



Phytoremediation vs. Mechanical/chemical treatment (cont.)

Limitations of phytoremediation (cont.)

- Plant tolerance to pollutant/conditions

  - Bigger problem with metals than organics
  - Can be alleviated using amendments, or treating hot spots by other method

- Bioavailability of contaminant

  - Bioavailability can be enhanced by amendments

So, when choose phytoremediation?

- Sufficient time available
- Pollution shallow enough
- Pollutant concentrations not phytotoxic

- $$ limited

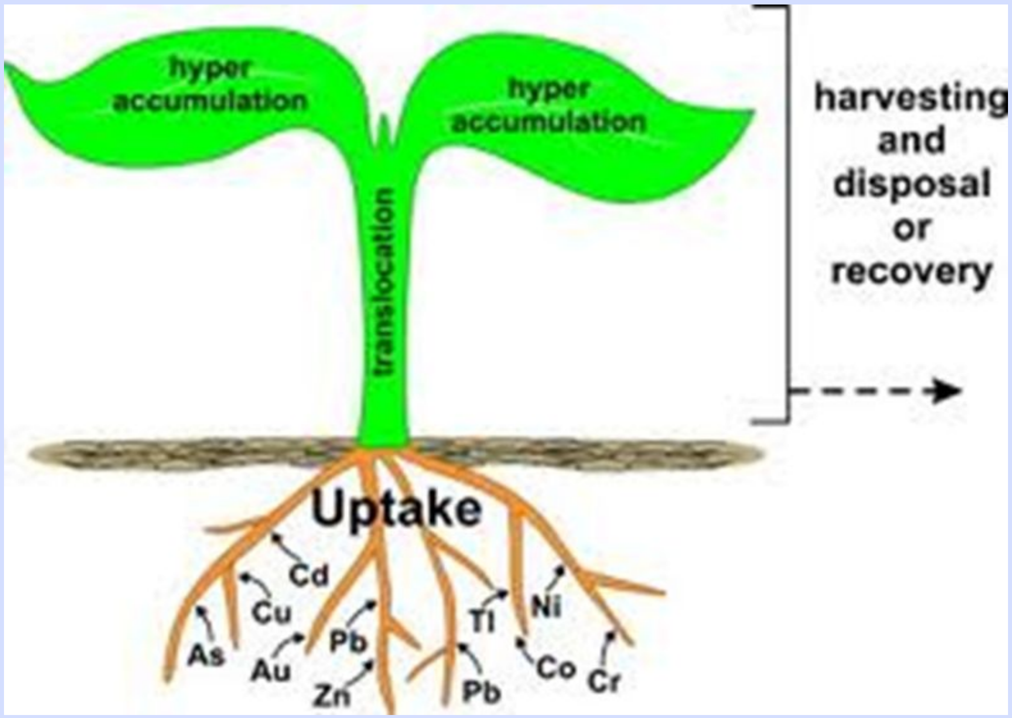
Note: *Phyto may be used in conjunction with other remediation methods*

For very large quantities of mildly contaminated substrate:
phytoremediation <u>only</u> cost-effective option

Techniques/strategies of phytoremediation

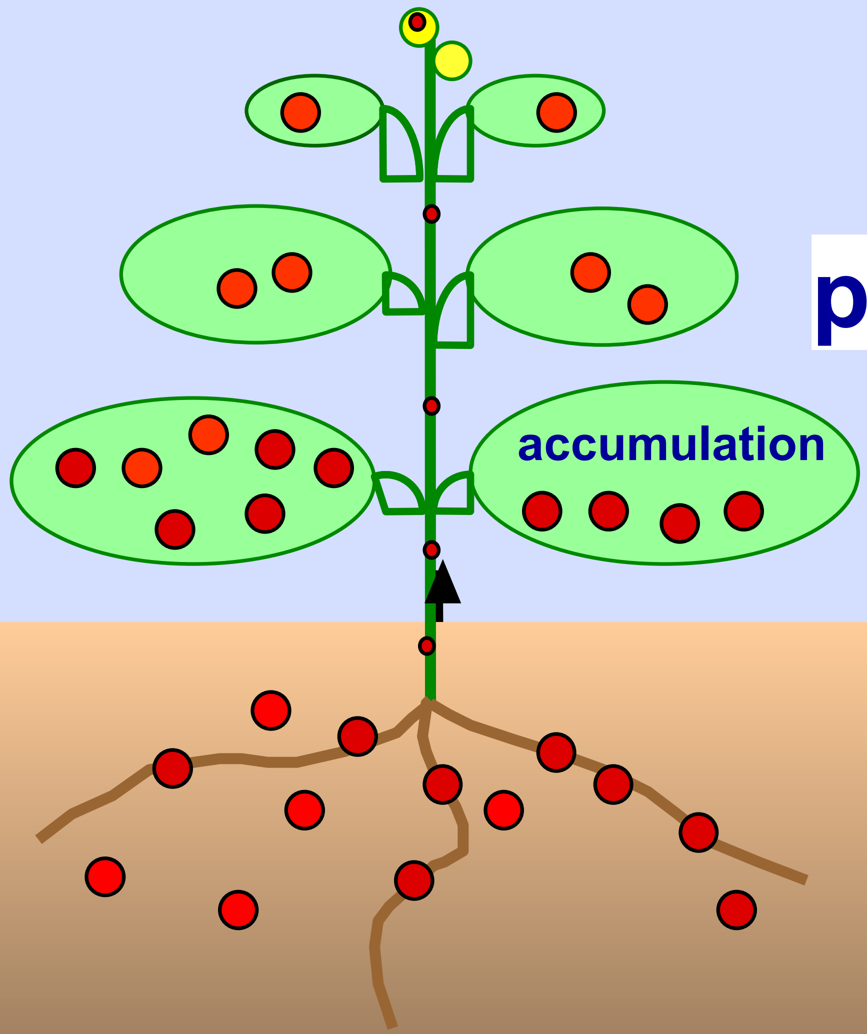
- phytoextraction (or phytoaccumulation),
- phytostabilization,
- Phytostimulation,
- phytofiltration,
- phytovolatilization,
- and phytodegradation

Phytoextraction



Phytoextraction (also known as phytoaccumulation, phytoabsorption or phytosequestration) is the uptake of contaminants from soil or water by plant roots and their translocation to and accumulation in aboveground biomass i.e., shoots.

Phytoremediation processes



phytoextraction

- **Phytoextraction**: pollutant accumulated in harvestable plant tissues

mainly inorganics:

metals

metalloids

radionuclides

Plant biomass may be used

(e.g. to mine metals, or non-food industrial use)

or disposed after minimizing volume

(incineration, composting)

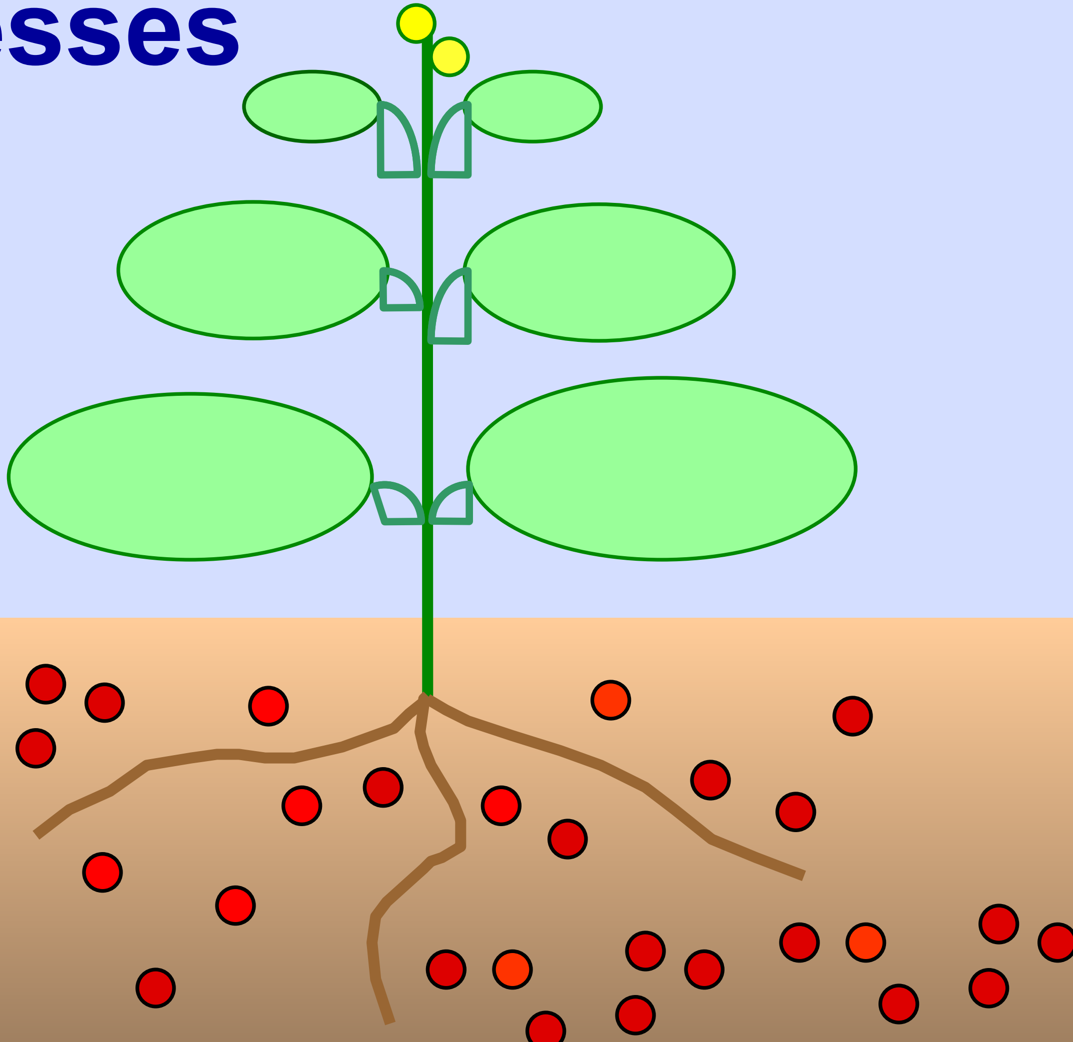
Phytostabilization

- Phytostabilization or phytoimmobilization is the use of certain plants for stabilization of contaminants in contaminated soils
- is used to reduce the mobility and bioavailability of pollutants in the environment, thus preventing their migration to groundwater or their entry into the food chain.

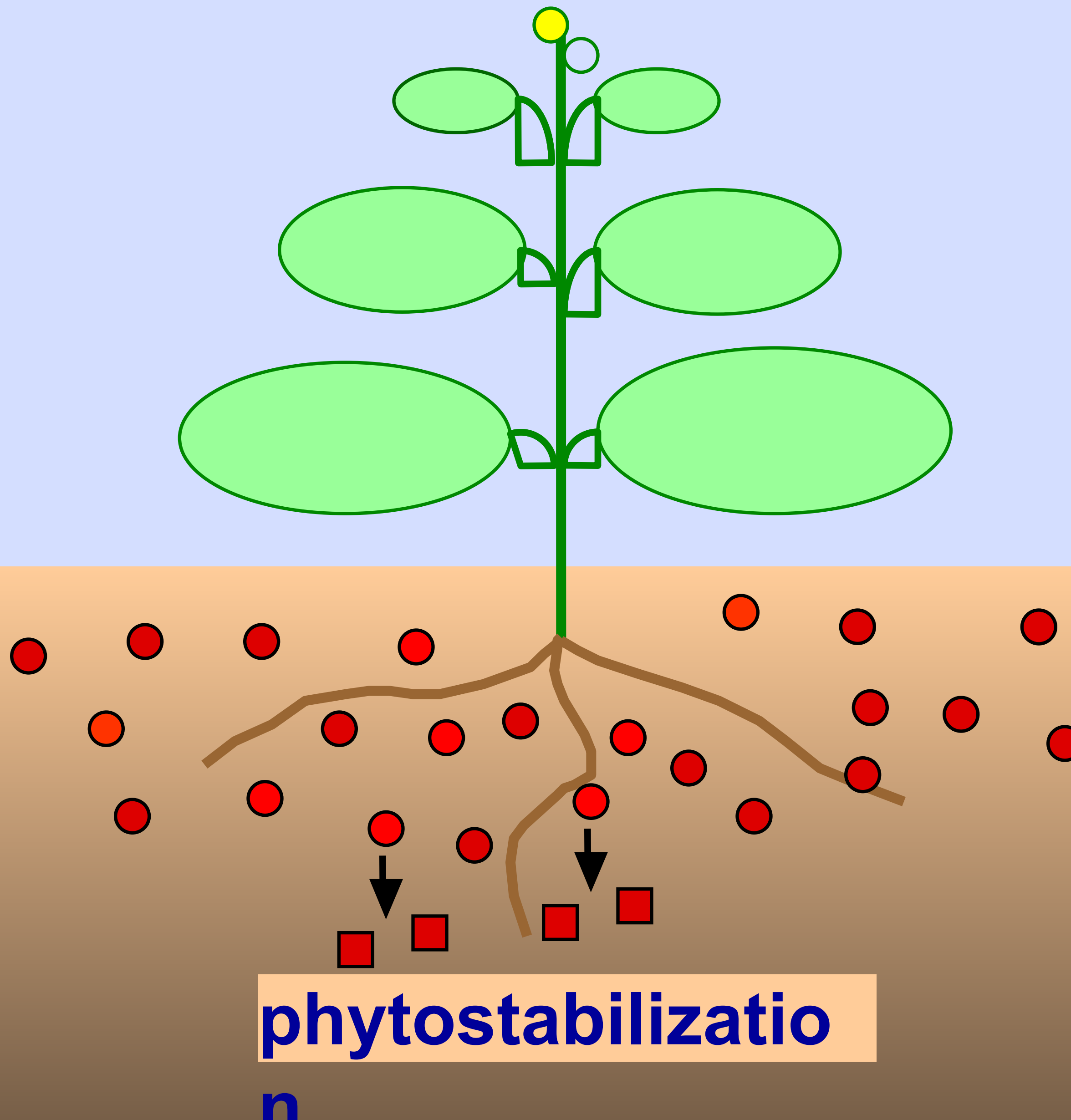
Plants can immobilize heavy metals in soils through:

- sorption by roots,
- precipitation,
- complexation or metal valence reduction in rhizosphere etc.

Phytoremediation processes



Phytoremediation processes



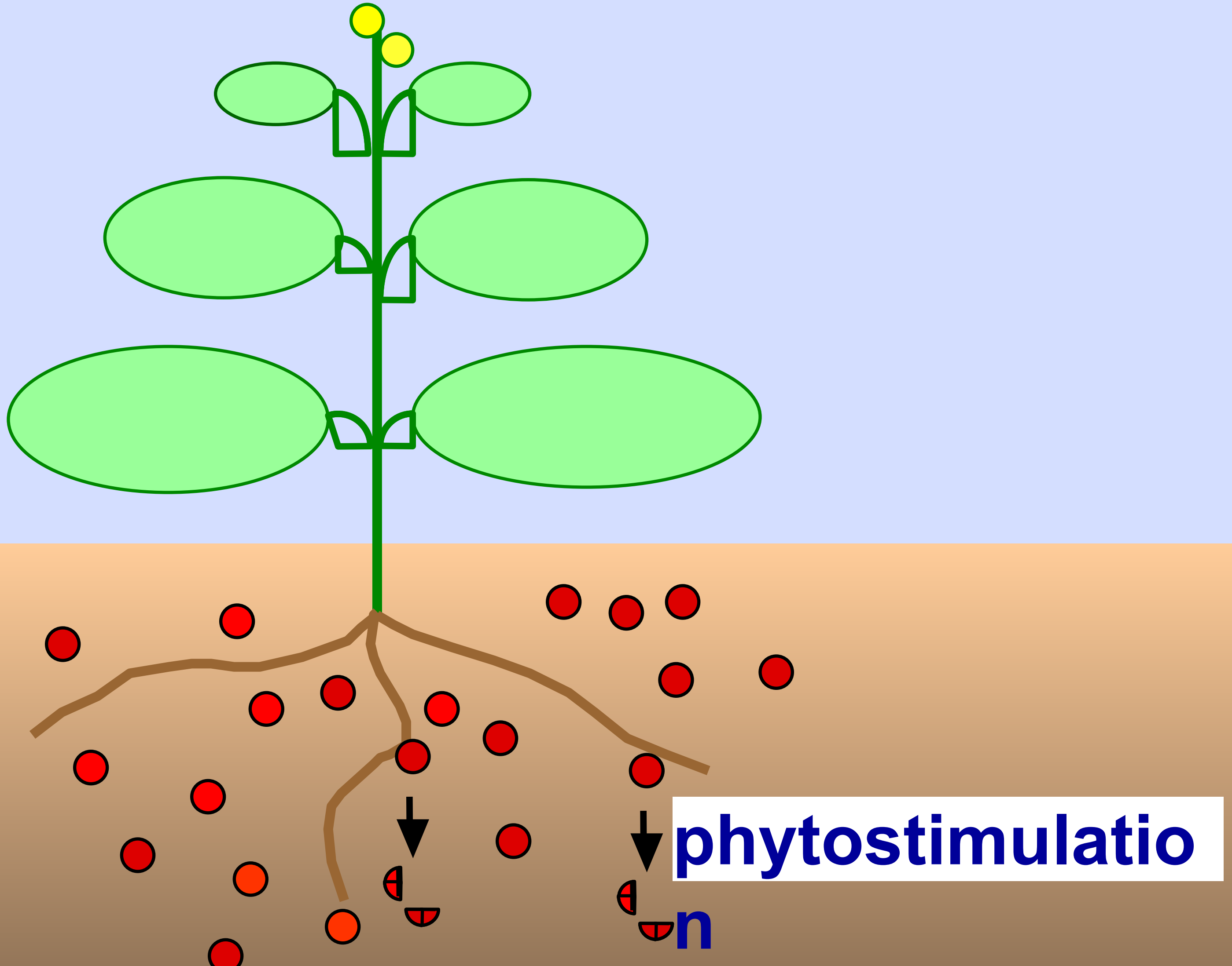
- **Phytostabilization**:

pollutant immobilized in soil

- Metals
- Non-bioavailable organics

1. Plants reduce leaching, erosion, runoff
 pollutant stays in place
2. Plants + microbes may transform pollutant to less bioavailable form (e.g. metal precipitation on roots)

Phytoremediation processes



- **Phytostimulation**: plant roots stimulate degradation of pollutant by rhizosphere microbes

Organics
e.g. PCBs, PAHs

bacteria, fungi

Phytodegradation

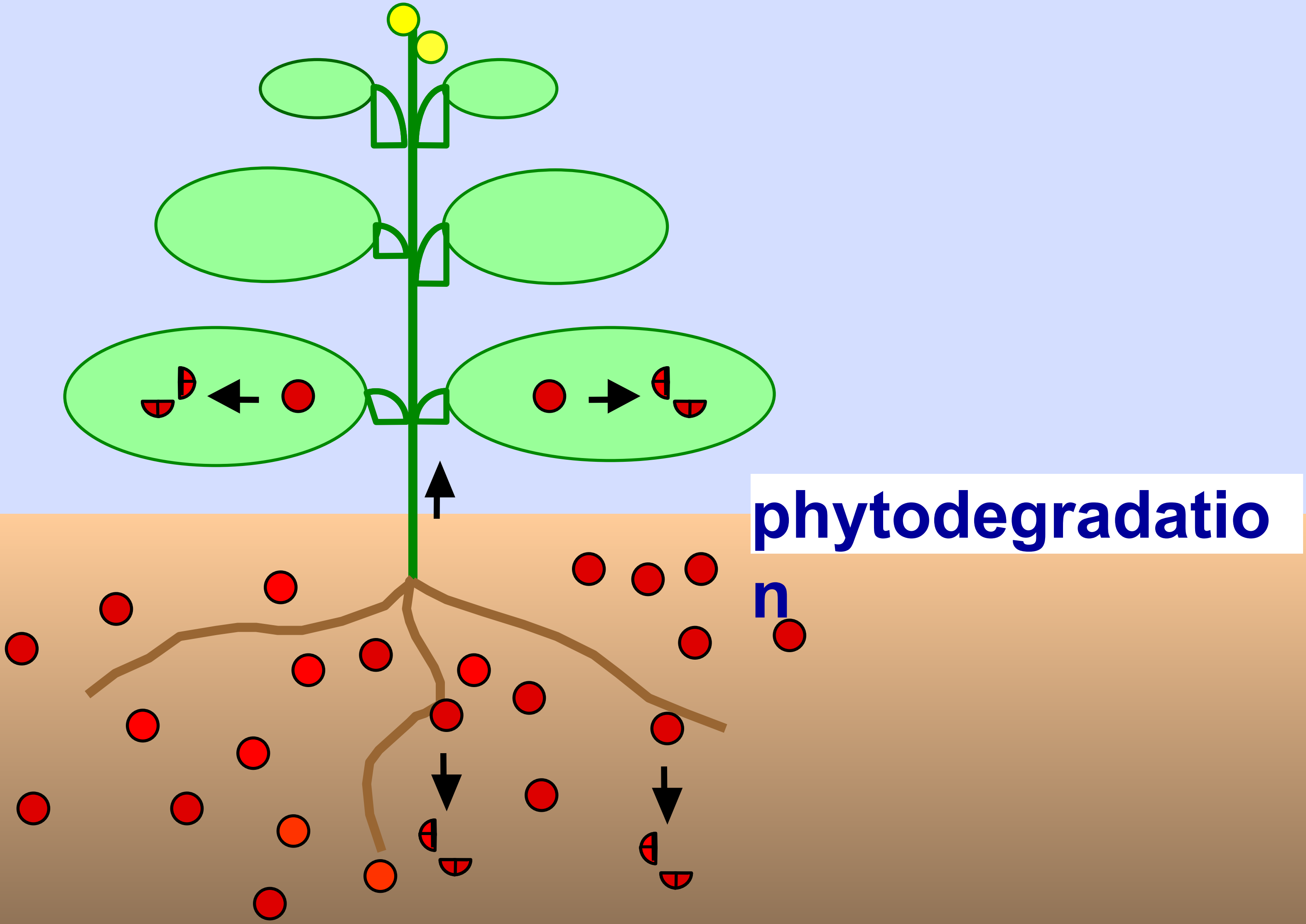
Phytodegradation is the degradation of organic pollutants by plants with the help of enzymes such as dehalogenase and oxygenase; it is not dependent on rhizospheric microorganisms .

Plants can accumulate organic xenobiotics from polluted environments and detoxify them through their metabolic activities (‘‘Green Liver’’ for the biosphere).

<u>Limitations:</u>

Heavy metals are non-biodegradable.

Phytoremediation processes



- **Phytodegradation**:
  plants degrade pollutant, with/without uptake, translocation

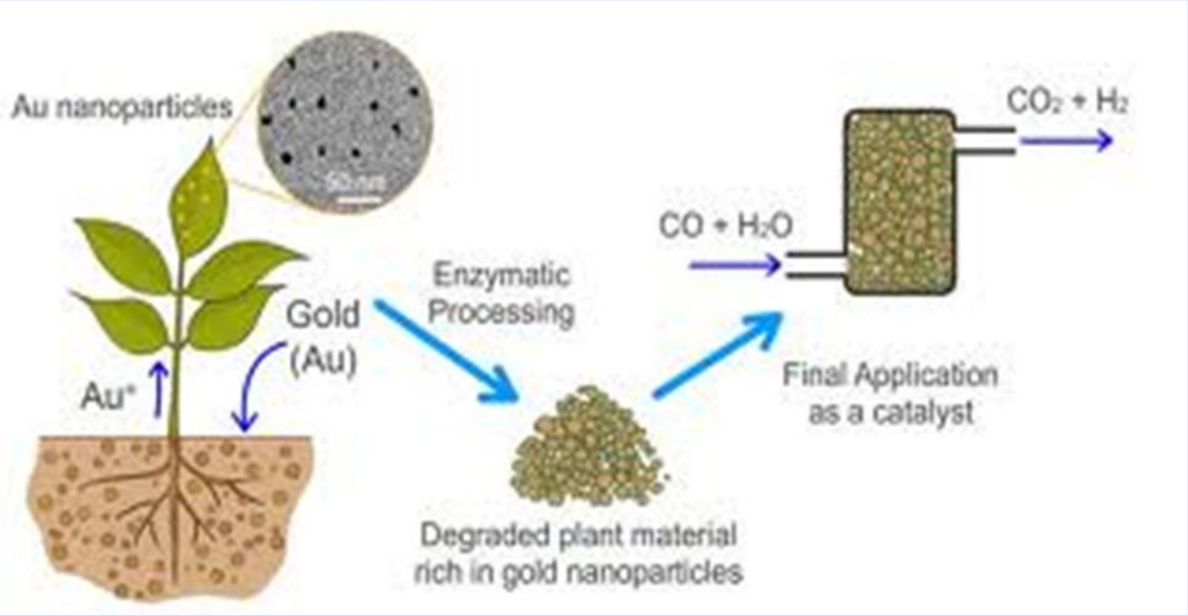
↓

Via enzymes, → in tissues or in root exudate

e.g. oxygenases
nitroreductase

Certain organics
e.g. TCE, TNT, atrazine

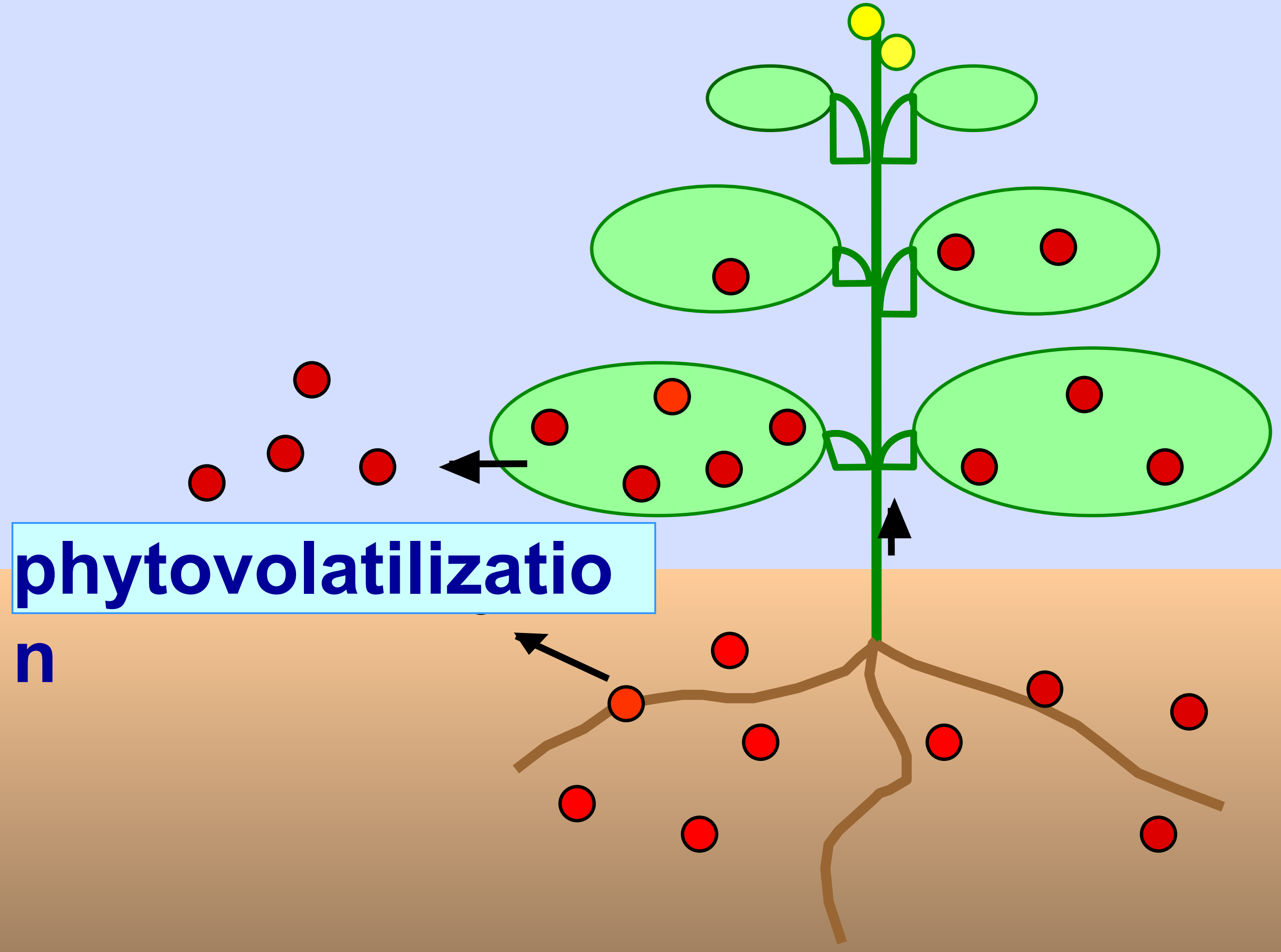
Phytovolatilization



Phytovolatilization is the uptake of pollutants from soil by plants, their conversion to volatile form and subsequent release into the atmosphere. This technique can be used for organic pollutants and some heavy metals like Hg and Se.

Disadvantage:
use is limited by the fact that it does not remove the pollutant completely; only it is transferred from one segment (soil) to another (atmosphere) from where it can be redeposited.

Phytoremediation processes



- **Phytovolatilization**: pollutant released in volatile form into the air

↓

some metal(loid)s: Se, As, Hg

some volatile organics: TCE, MTBE

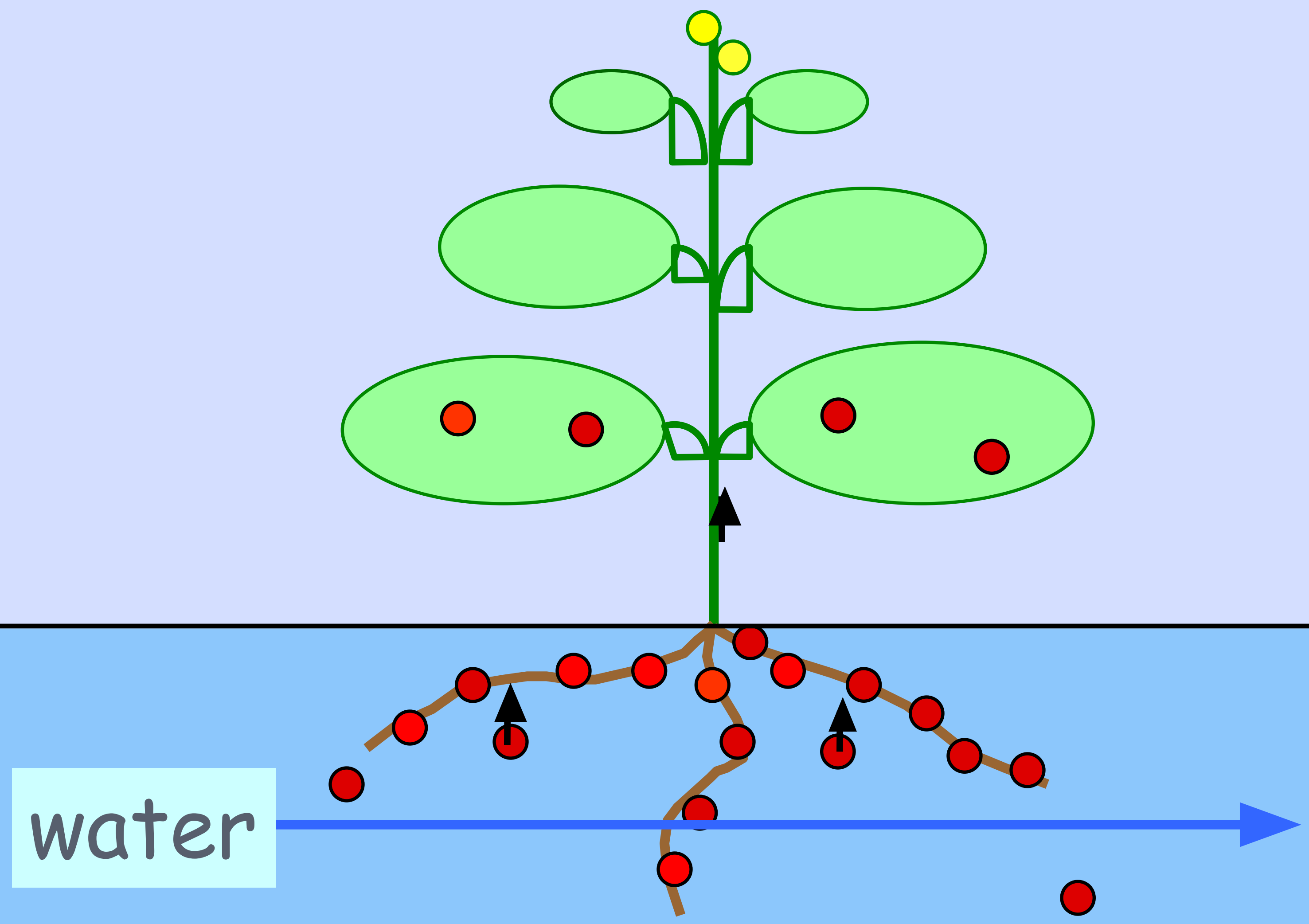
Rhizodegradation

Rhizodegradation refers to the breakdown of organic pollutants in the soil by microorganisms in the rhizosphere. Rhizosphere extends about 1 mm around the root and is under the influence of the plant.

Plants can stimulate microbial activity about 10–100 times higher in the rhizosphere by the secretion of exudates containing carbohydrates, amino acids, flavonoids.

The release of nutrients-containing exudates by plant roots provides carbon and nitrogen sources to the soil microbes and creates a nutrient-rich environment in which microbial activity is stimulated.

Rhizofiltration



- **Rhizofiltration**: pollutant removed from water by plant roots in hydroponic system

for inorganics

metals

metalloids

radionuclides

Plant roots & shoots harvestable

(may be used to mine metals)

or disposed after minimizing volume

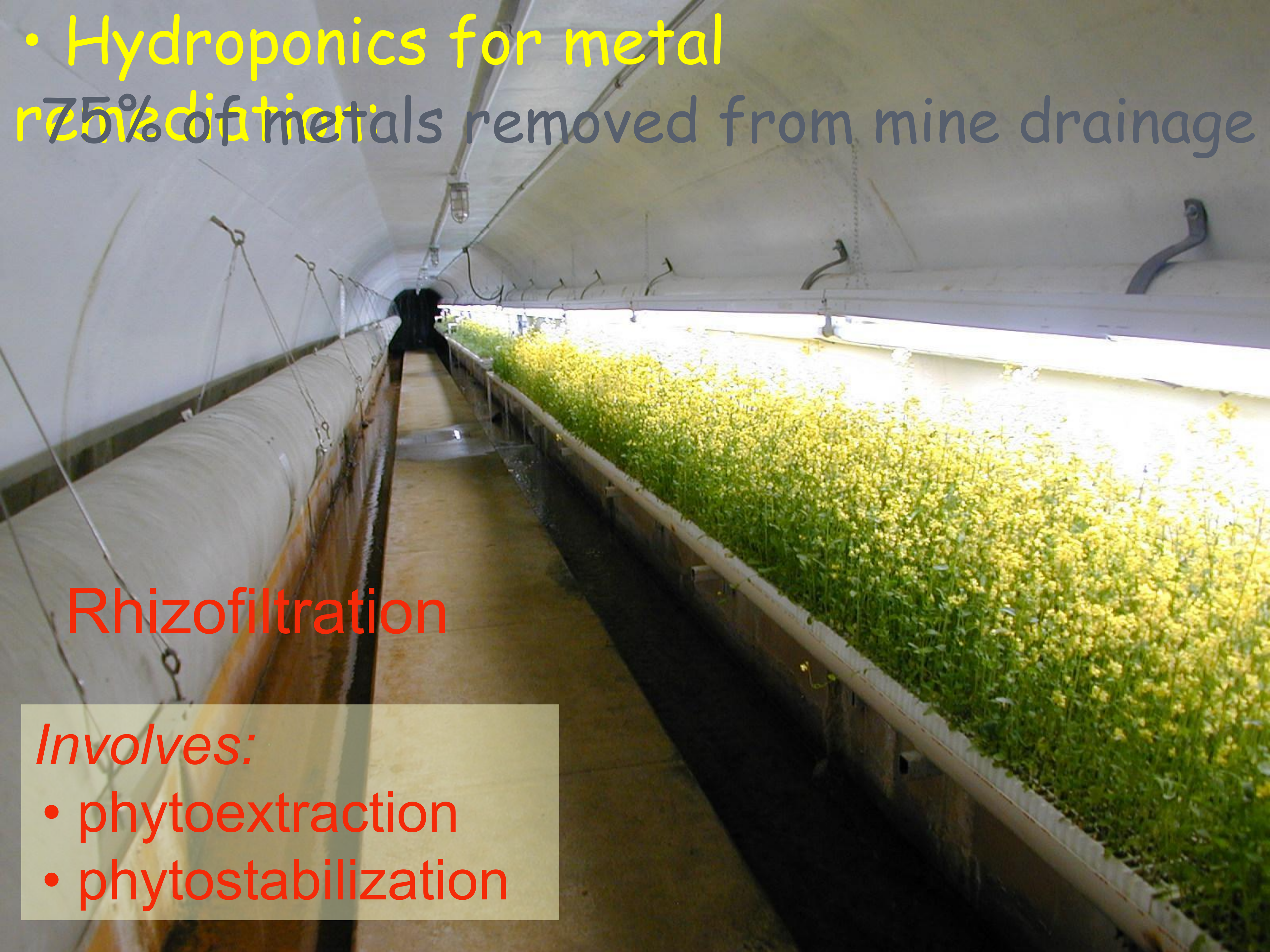
Phytofiltration

Phytofiltration is the removal of pollutants from contaminated surface waters or waste waters by plants.

Phytofiltration may be:

- <u>rhizofiltration</u> (use of plant roots);
- <u>blastofiltration</u> (use of seedlings) or

<u>caulofiltration</u> (use of excised plant shoots; Latin caulis = shoot)


• Hydroponics for metal remediation:
75% of metals removed from mine drainage
Rhizofiltration
Involves:
• phytoextraction
• phytostabilization

- Constructed wetland for Se remediation:

75% of Se removed from ag drainage water

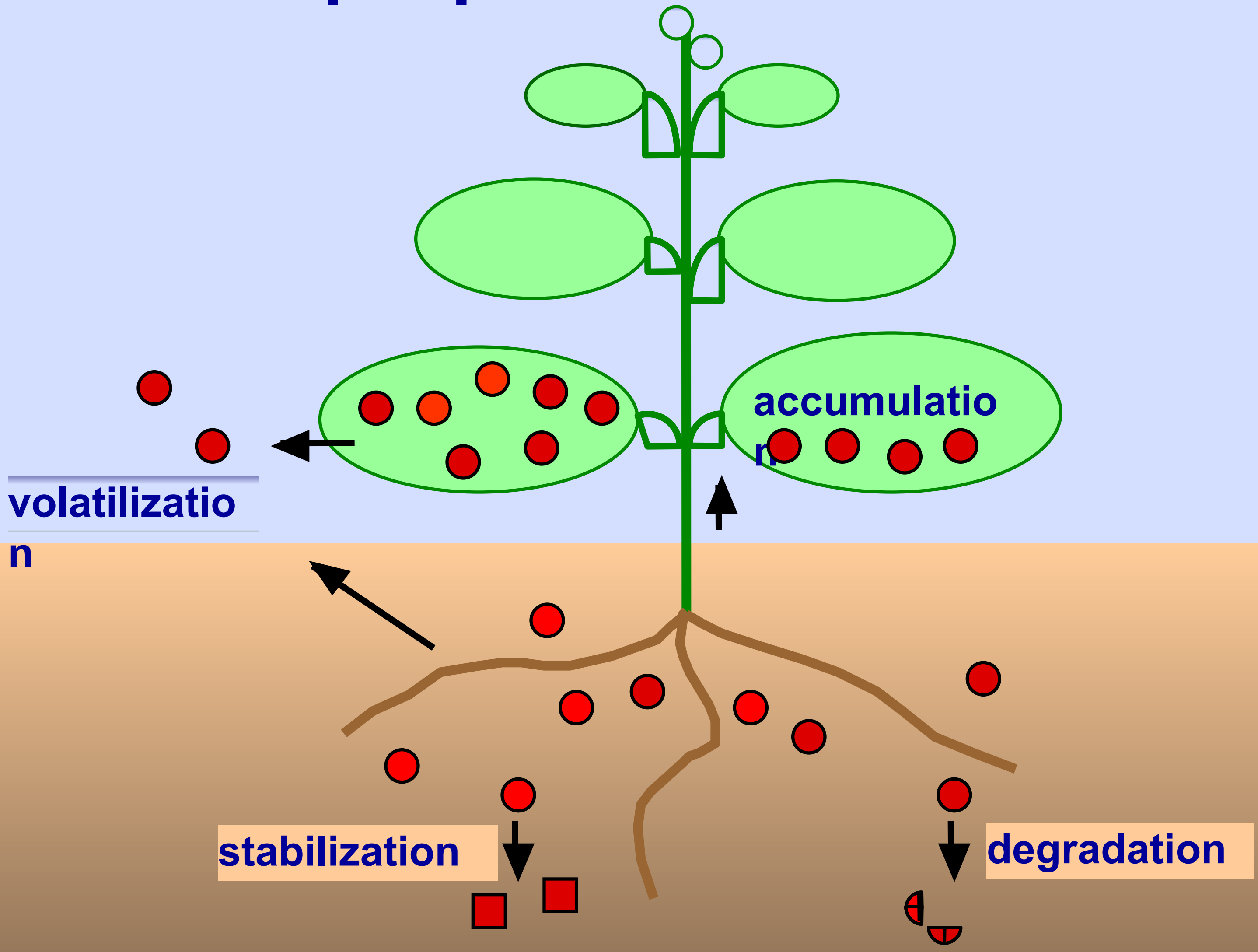
Involves:

- phytoextraction
- phytovolatilization
- phytostabilization
- (rhizofiltration)
- (phytostimulation)

Phytodesalination

Phytodesalination refers to the use of halophytic plants for removal of salts from salt-affected soils in order to enable them for supporting normal plant growth.

Phytoremediation applications may involve multiple processes at once



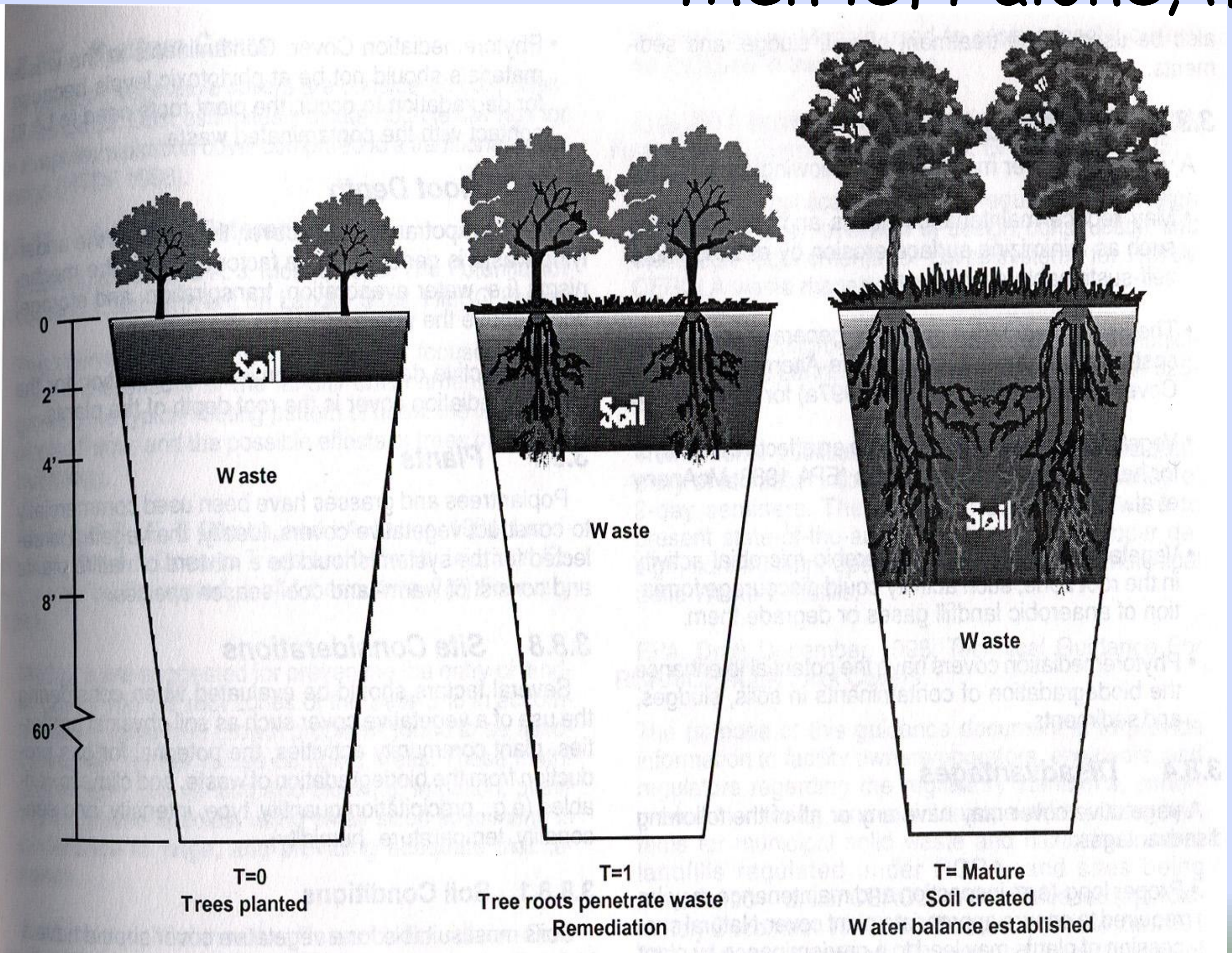
Summary of phytoremediation techniques

Table 3
Summary of the different techniques of phytoremediation.

Technique	Description
Phytoextraction	Accumulation of pollutants in harvestable biomass i.e., shoots
Phytofiltration	Sequestration of pollutants from contaminated waters by plants
Phytostabilization	Limiting the mobility and bioavailability of pollutants in soil by plant roots
Phytovolatilization	Conversion of pollutants to volatile form and their subsequent release to the atmosphere
Phytodegradation	Degradation of organic xenobiotics by plant enzymes within plant tissues
Rhizodegradation	Degradation of organic xenobiotics in the rhizosphere by rhizospheric microorganisms
Phytodesalination	Removal of excess salts from saline soils by halophytes

- **Natural attenuation**: polluted site left alone but monitored

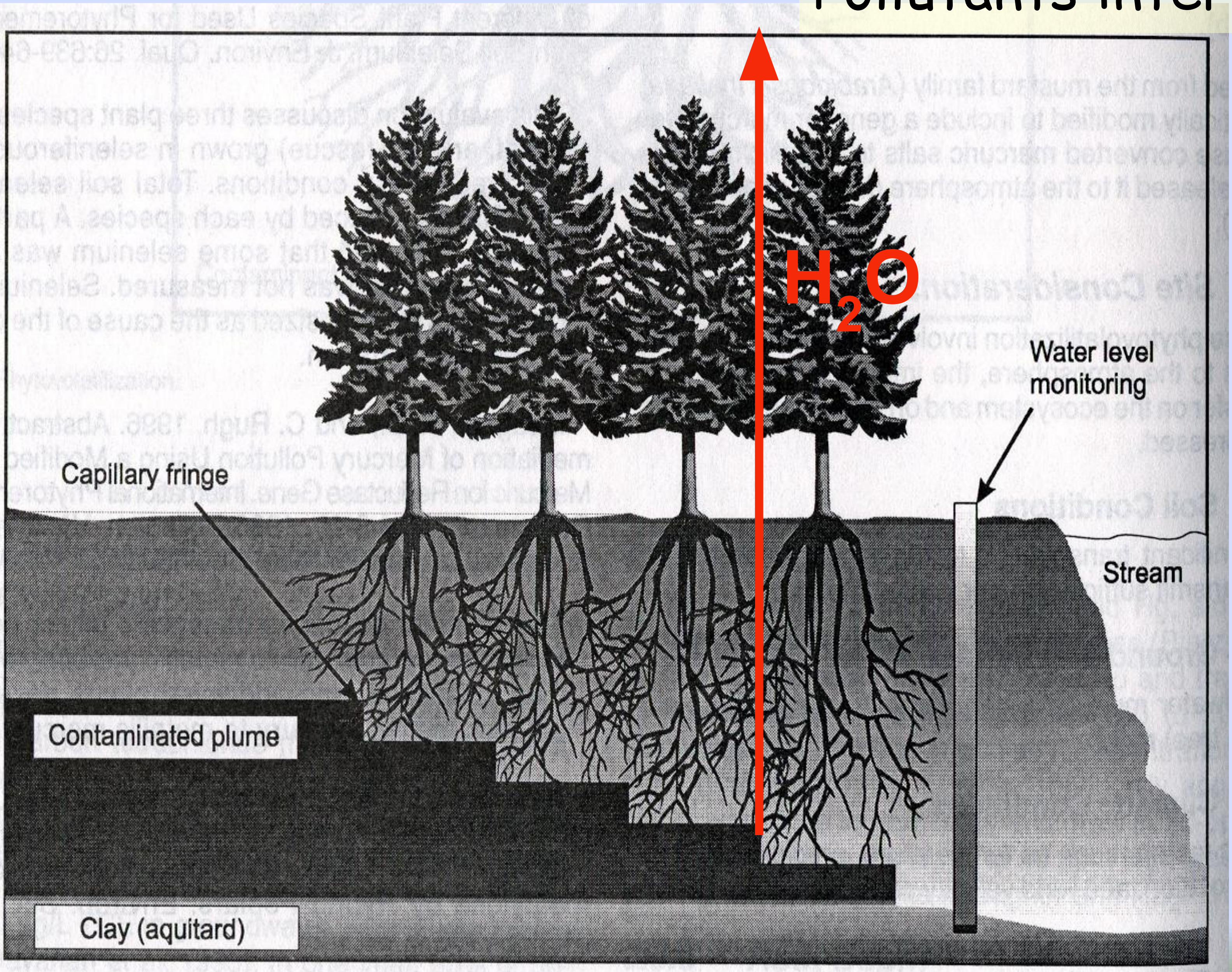
- **Vegetative cap**: polluted site revegetated, then left alone, monitored



with/without adding clean topsoil

Hydraulic barrier

Water flow redirected
Pollutants intercepted



Heavy metals problems in the context of PHYTOREMEDIATION

Heavy metals & organic compounds

- heavy metals originate from extraction of ores and processing
- *heavy metals are non-biodegradable,*
- *they accumulate in the environment*
- *subsequently contaminate the food chain.*
- heavy metals cause toxicological effects on soil microbes, which may lead to a decrease in their numbers and activities

This contamination poses a risk to environmental and human health.

Essential HM: Fe, Mn, Cu, Zn, and Ni

Non-essential HM: Cd, Pb, As, Hg, and Cr.

Sources of heavy metals in the environment

Natural sources

- weathering of minerals,
- erosion and volcanic activity

Anthropogenic sources

- mining,
- smelting,
- electroplating,
- use of pesticides and (phosphate)
- fertilizers as well as biosolids in agriculture,
- sludge dumping,
- industrial discharge,
- atmospheric deposition, etc.

Sources of HM

Table 1
Anthropogenic sources of specific heavy metals in the environment.

Heavy metal	Sources
As	Pesticides and wood preservatives
Cd	Paints and pigments, plastic stabilizers, electroplating, incineration of cadmium-containing plastics, phosphate fertilizers
Cr	Tanneries, steel industries, fly ash
Cu	Pesticides, fertilizers
Hg	Release from Au–Ag mining and coal combustion, medical waste
Ni	Industrial effluents, kitchen appliances, surgical instruments, steel alloys, automobile batteries
Pb	Aerial emission from combustion of leaded petrol, battery manufacture, herbicides and insecticides

Harmful effects of heavy metals on human health

- are toxic and can cause undesirable effects and severe problems even at very low concentrations
- cause oxidative stress
- can replace essential metals in pigments or enzymes disrupting their function
- the most problematic heavy metals are Hg, Cd, Pb, As, Cu, Zn, Sn, and Cr

Harmful effects of HM

Table 2
Harmful effects of specific heavy metals on human health.

Heavy metal	Harmful effects
As	As (as arsenate) is an analogue of phosphate and thus interferes with essential cellular processes such as oxidative phosphorylation and ATP synthesis
Cd	Carcinogenic, mutagenic, and teratogenic; endocrine disruptor; interferes with calcium regulation in biological systems; causes renal failure and chronic anemia
Cr	Causes hair loss
Cu	Elevated levels have been found to cause brain and kidney damage, liver cirrhosis and chronic anemia, stomach and intestinal irritation
Hg	Anxiety, autoimmune diseases, depression, difficulty with balance, drowsiness, fatigue, hair loss, insomnia, irritability, memory loss, recurrent infections, restlessness, vision disturbances, tremors, temper outbursts, ulcers and damage to brain, kidney and lungs
Ni	Allergic dermatitis known as nickel itch; inhalation can cause cancer of the lungs, nose, and sinuses; cancers of the throat and stomach have also been attributed to its inhalation; hematotoxic, immunotoxic, neurotoxic, genotoxic, reproductive toxic, pulmonary toxic, nephrotoxic, and hepatotoxic; causes hair loss
Pb	Its poisoning causes problems in children such as impaired development, reduced intelligence, loss of short-term memory, learning disabilities and coordination problems; causes renal failure; increased risk for development of cardiovascular disease.
Zn	Over dosage can cause dizziness and fatigue.

Cleanup of heavy metal-contaminated soils

Cleanup of heavy metal-contaminated soils is utmost necessary in order to minimize their impact on the ecosystems.

The conventional remediation methods include in situ vitrification, soil incineration, excavation and landfill, soil washing, soil flushing, solidification, and stabilization of electro-kinetic systems

<u>Disadvantages</u>: high costs, intensive labor, irreversible changes in soil properties and disturbance of native soil microflora, secondary pollution etc.

Phytoremediation – a green solution to the HM problem

‘‘Phytoremediation basically refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environments’’ (Greipsson, 2011).

- It can be used for removal of heavy metals and radionuclides as well as for organic pollutants (such as, polynuclear aromatic hydrocarbons, polychlorinated biphenyls, and pesticides).
- It is a novel, cost-effective, efficient, environment- and eco-friendly, in situ applicable, and solar-driven remediation strategy.
- Plants generally handle the contaminants without affecting topsoil, uptake pollutants from the environment .
- low installation and maintenance costs.
- The establishment of vegetation on polluted soils also helps prevent erosion and metal leaching

Purpose of phytoremediation

- risk containment (phytostabilization);
- phytoextraction of metals with market value such as Ni, Tl and Au;
- durable land management where phytoextraction gradually improves soil quality for subsequent cultivation of crops with higher market value.
- Furthermore, fast-growing and high-biomass producing plants such as willow, poplar and Jatropha could be used for both phytoremediation and energy production.

Phytoextraction of heavy metals

The main and most useful phytoremediation technique for removal of HM and metalloids from polluted soils, sediments or water. The efficiency depends on many factors like bioavailability of the heavy metals in soil, soil properties, speciation of the heavy metals and plant species concerned. Plants suitable for phytoextraction should ideally have the following characteristics:

- High growth rate.
- Production of more above-ground biomass.
- Widely distributed and highly branched root system.
- More accumulation of the target heavy metals from soil.
- Translocation of the accumulated heavy metals from roots to shoots.
- Tolerance to the toxic effects of the target heavy metals.
- Good adaptation to prevailing environmental and climatic conditions.
- Resistance to pathogens and pests.
- Easy cultivation and harvest.
- Repulsion to herbivores to avoid food chain contamination.

Phytoextraction: two key factors

The phytoextraction potential of a plant species is mainly determined by two key factors i.e., shoot metal concentration and shoot biomass. *Two different approaches have been tested for phytoextraction of heavy metals*:

(1) The use of ***hyperaccumulators***, which produce comparatively less aboveground biomass but accumulate ***target heavy metals*** to a greater extent;

(2) The application of other plants, such as Brassica juncea (Indian mustard), which ***accumulate target heavy metals to a lesser extent but produce more aboveground biomass*** so that overall accumulation is comparable to that of hyperaccumulators due to production of more biomass.

Bioavailability of HM in soils

Chemical composition and sorption properties of soil influence the mobility and bioavailability of metals. Low bioavailability is a major limiting factor for phytoextraction of contaminants. *Strong binding of heavy metals to soil particles or precipitation causes a significant fraction of soil heavy metals* ***insoluble*** *and therefore mainly unavailable for uptake by plants.*

Bioavailability of heavy metals/metalloids in soil:

- readily bioavailable (Cd, Ni, Zn, As, Se, Cu);
- moderately bioavailable (Co, Mn, Fe)
- and least bioavailable (Pb, Cr, U)

However, plants have developed certain mechanisms for solubilizing heavy metals in soil. Plant roots secrete metal-mobilizing substances in the rhizosphere called ***phytosiderophores*** . *Secretion of H+ ions by roots can acidify the rhizosphere and increase metal dissolution. H+ ions can displace heavy metal cations adsorbed to soil particles*

Phytoextraction: two modes

<u>Natural conditions:</u> no soil amendm.

<u>Induced or chelate assisted phytoextraction:</u> different chelating agents such as EDTA (**etylendiamintetraacetic acid**), citric acid, elemental sulfur, and $(NH_4)_2SO_4$ are added to soil to increase the bioavailability of heavy metals in soil for uptake by plants.

Bioavailability of the heavy metals can also be increased by lowering soil pH since metal salts are soluble in acidic media rather than in basic media. However, these chemical treatments can cause secondary pollution problems.

Use of citric acid as a chelating agent could be promising because it has a natural origin and is easily biodegraded in soil.

Metallophytes

Metallophytes are plants that are specifically adapted to and thrive in heavy metal-rich soils.

Metallophytes are divided into three categories:

1. ***Metal excluders*** accumulate heavy metals from substrate into their roots but restrict their transport and entry into their aerial parts. Such plants have a low potential for metal extraction but may be efficient for phytostabilization purposes.*,*

2. ***Metal indicators*** accumulate heavy metals in their aerial parts and reflect heavy metal concentrations in the substrate

3. ***Metal hyperaccumulators*** are plants, which can concentrate heavy metals in their aboveground tissues to levels far exceeding those present in the soils or non-accumulating plants. These plants are concentrated in the plant family *Brassicaceae*. Their use especially in mining regions, either alone or in combination with microorganisms, for phytoremediation of heavy metal-contaminated soils is an attractive idea.

Hyperaccumulation in plants

The following concentration criteria for different metals and metalloids in dried foliage with plants growing in their natural habitats are proposed:

- 100 mg/kg for Cd, Se and Tl;
- 300 mg/kg for Co, Cu and Cr;
- 1000 mg/kg for Ni, Pb and As;
- 3000 mg/kg for Zn;
- 10000 mg/kg for Mn.

Generally, hyperaccumulators achieve 100-fold higher shoot metal concentration (without yield reduction) compared to crop plants or common nonaccumulator plants.

Hyperaccumulators achieve a shoot-to-root metal concentration ratio (called ***translocation factor, TF***) of greater than 1.

Table 4
List of some hyperaccumulator plants.

Plant species	Metal	Metal accumulation (mg kg^{-1})	Reference
Alyssum bertolonii	Ni	10900	Li et al. (2003)
Alyssum caricum	Ni	12500	Li et al. (2003)
Alyssum corsicum	Ni	18100	Li et al. (2003)
Alyssum heldreichii	Ni	11800	Bani et al. (2010)
Alyssum markgrafii	Ni	19100	Bani et al. (2010)
Alyssum murale	Ni	4730–20100	Bani et al. (2010)
		15000	Li et al. (2003)
Alyssum pterocarpum	Ni	13500	Li et al. (2003)
Alyssum serpyllifolium	Ni	10000	Prasad (2005)
Azolla pinnata	Cd	740	Rai (2008)
Berkheya coddii	Ni	18000	Mesjasz-Przybylowicz et al. (2004)
Corrigiola telephiifolia	As	2110	(Garcia-Salgado et al., 2012)
Eleocharis acicularis	Cu	20200	Sakakibara et al. (2011)
	Zn	11200	
	Cd	239	
	As	1470	
Euphorbia cheiradenia	Pb	1138	Chehregani and Malayeri (2007)
Isatis pinnatiloba	Ni	1441	Altinozlu et al. (2012)
Pteris biaurita	As	~2000	Srivastava et al. (2006)
Pteris cretica	As	~1800	Srivastava et al. (2006)
		2200–3030	Zhao et al. (2002)
Pteris quadriaurita	As	~2900	Srivastava et al. (2006)
Pteris ryukyuensis	As	3647	Srivastava et al. (2006)
Pteris vittata	As	8331	Kalve et al. (2011)
		~1000	Baldwin and Butcher (2007)
	Cr	20675	Kalve et al. (2011)
Rorippa globosa	Cd	>100	Wei et al. (2008)
Schima superba	Mn	62412.3	Yang et al. (2008)
Solanum photeinocarpum	Cd	158	Zhang et al. (2011)
Thlaspi caerulescens	Cd	263	Lombi et al. (2001)

Hyperaccumulators

The most commonly postulated hypothesis regarding the reason or advantage of metal hyperaccumulation in plants is elemental defense against herbivores (by making leaves unpalatable or toxic) and pathogens.

Hyperaccumulators can be used for phytoremediation of toxic and hazardous heavy metals as well as for phytomining of precious heavy metals (such as Au, Pd and Pt). Some plants have natural ability of hyperaccumulation for specific heavy metals.

Quantification of phytoextraction efficiency

Bioconcentration factor indicates the efficiency of a plant species in accumulating a metal into its tissues from the surrounding environment. It is calculated as follows

$$\text{Bioconcentration Factor (BCF)} = \frac{C_{\text{harvested tissue}}}{C_{\text{soil}}} \qquad (1)$$

where $C_{\text{harvested tissue}}$ is the concentration of the target metal in the plant harvested tissue and C_{soil} is the concentration of the same metal in the soil (substrate).

Translocation factor indicates the efficiency of the plant in translocating the accumulated metal from its roots to shoots. It is calculated as follows

$$\text{Translocation Factor (TF)} = \frac{C_{\text{shoot}}}{C_{\text{root}}} \qquad (2)$$

where C_{shoot} is concentration of the metal in plant shoots and C_{root} is concentration of the metal in plant roots.

Quantification of phytoextraction efficiency

Accumulation factor (A) can also be represented in percent according to the following equation

$$\text{Accumulation Factor}(A) = \frac{C_{\text{plant tissue}}}{C_{\text{soil}}} \times 100 \quad (3)$$

where A is accumulation factor %, $C_{\text{plant tissue}}$ is metal concentration in plant tissue and C_{soil} is metal concentration in soil. Similarly, translocation factor can also be represented in percent according to the following equation.

$$\text{TF} = \frac{C_{\text{aerial parts}}}{C_{\text{roots}}} \times 100 \quad (4)$$

Fate of plants used for phytoextraction

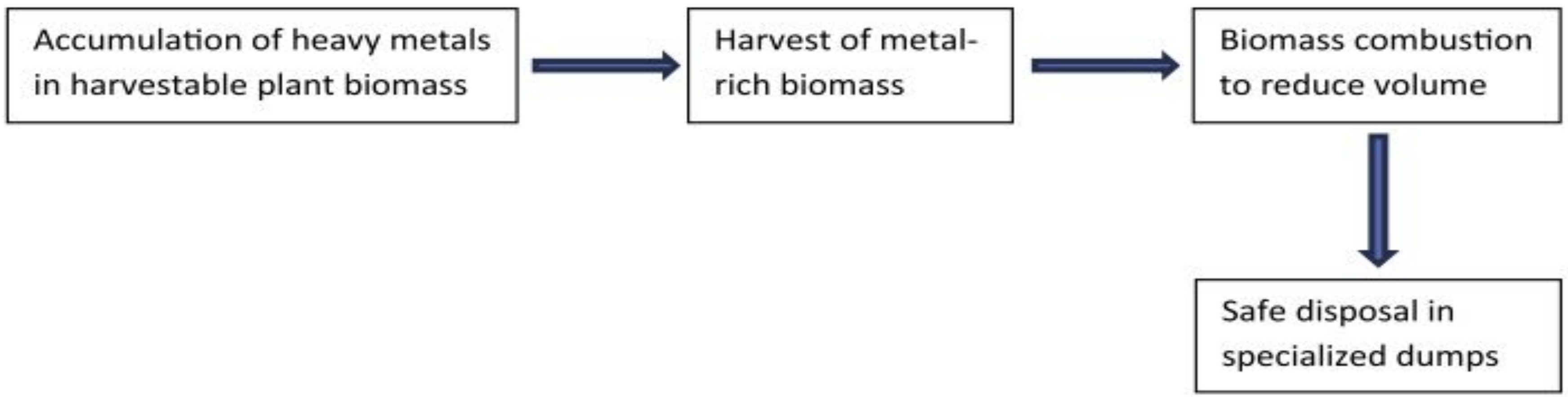


Fig. 1. Main route of post-harvest treatment of phytoremediator plants.

Phytomining

Advantages:

- can be combusted to get energy and the remaining ash is considered as ‘‘bio-ore’’;

-phytomining is the sale of energy from combustion of the biomass;

-bio-ore can be processed for the recovery or extraction of the heavy metals;

-Processing bio-ores contributes less SOx emissions to the atmosphere;

-Phytomining has been commercially used for Ni and it is believed that it is less expensive than the conventional extraction methods.

Use of constructed wetlands for phytoremediation

Constructed wetlands are used for clean-up of effluents and drainage waters. Aquatic macrophytes are more suitable for wastewater treatment than terrestrial plants due to their faster growth, production of more biomass and relative higher ability of pollutant uptake.

Poplar (Populus spp.) and willow (Salix spp.) can be used on the edge. *Water hyacinth (Eichhornia crassipes*) has been used for phytoremediation of heavy metals at constructed wetlands. Water lettuce (Pistia stratiotes) has been pointed out as a potential phytoremediator plant for *Mn* contaminated waters. Azolla (short doubling time 2–3 d) has nitrogen fixation ability and tolerance to and accumulation of a wide range of heavy metals.

Mechanism of heavy metals' uptake, translocation, and tolerance

Plants take heavy metals from soil solution into their roots. After entry into roots, heavy metal ions can either be stored in the roots or translocated to the shoots primarily through xylem vessels where they are mostly deposited in vacuoles.

The mechanism of phytoextraction of heavy metals has five basic aspects:

- mobilization of the heavy metals in soil,
- uptake of the metal ions by plant roots,
- translocation of the accumulated metals from roots to aerial tissues,
- sequestration of the metal ions in plant tissues
- and metal tolerance.

Mechanisms governing heavy metal tolerance in plant cells are cell wall binding, active transport of ions into the vacuole and chelation through the induction of metal-binding peptides and the formation of metal complexes.

Organic acids and amino acids are suggested as ligands for chelation of heavy metal ions because of the presence of donor atoms (S, N, and O) in their molecules.

Role of phytochelatins and metallothioneins in phytoextraction

The most important peptides/proteins involved in metal accumulation and tolerance are ***phytochelatins (PCs) and metallothioneins (MTs)****.* Plant PCs and MTs are rich in cysteine sulfhydryl groups, which bind and sequester heavy metal ions in very stable complexes. PCs are small glutathione-derived, enzymatically synthesized peptides, which bind metals and are principal part of the metal detoxification system in plants. They have the general structure of (c-glutamyl-cysteinyl) n -glycine where n = 2–11.

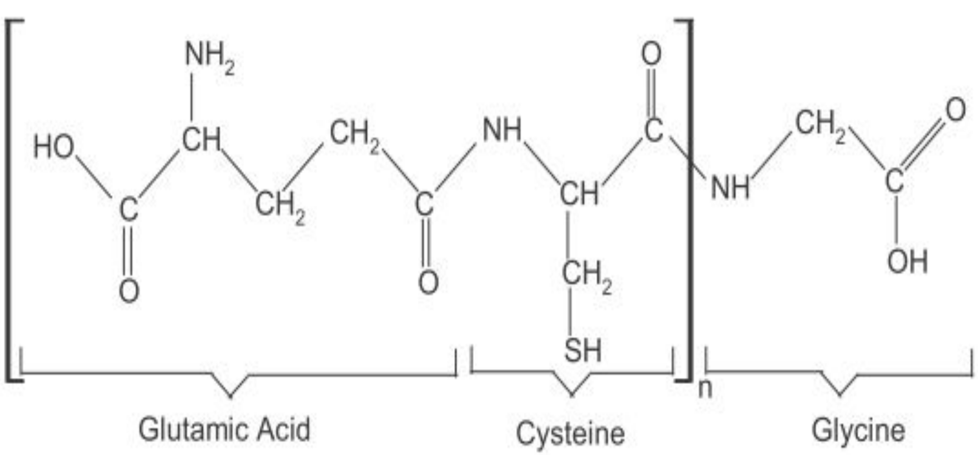


Fig. 2. Chemical structure of PCs (adapted from Seth, 2012).

MTs are gene-encoded, low molecular weight, metal-binding proteins, which can protect plants against the effects of toxic metal ions.

Limitations of phytoremediation

- Long time required
- Hyperaccumulators are usually limited by their slow growth rate and low biomass
- limited bioavailability of tightly bound fraction of metal ions from soil
- It is applicable to sites with low to moderate levels of metal contamination
- Risk of food chain contamination

Future trends in phytoremediation

Phytoremediation is a relatively recent field of research. Results in actual field can be different from those at laboratory or greenhouse conditions (different factors simultaneously play their role).

Factors that may affect phytoremediation in the field include:

- variations in temperature,
- nutrients,
- precipitation and moisture,
- plant pathogens and herbivory,
- uneven distribution of contaminants,
- soil type,
- soil pH,
- soil structure etc.

Future challenges in phytoremediation

Phytoremediation efficiency of different plants for specific target heavy metals has to be tested in field conditions in order to realize the feasibility of this technology for commercialization.

Identification of desirable traits in natural hyperaccumulators --- selection and breeding techniques. Thus different desirable traits can be combined into a single plant species.

In spite of the many challenges, phytoremediation is perceived as a green remediation technology with an expected great potential.

Interdisciplinary nature of phytoremediation research

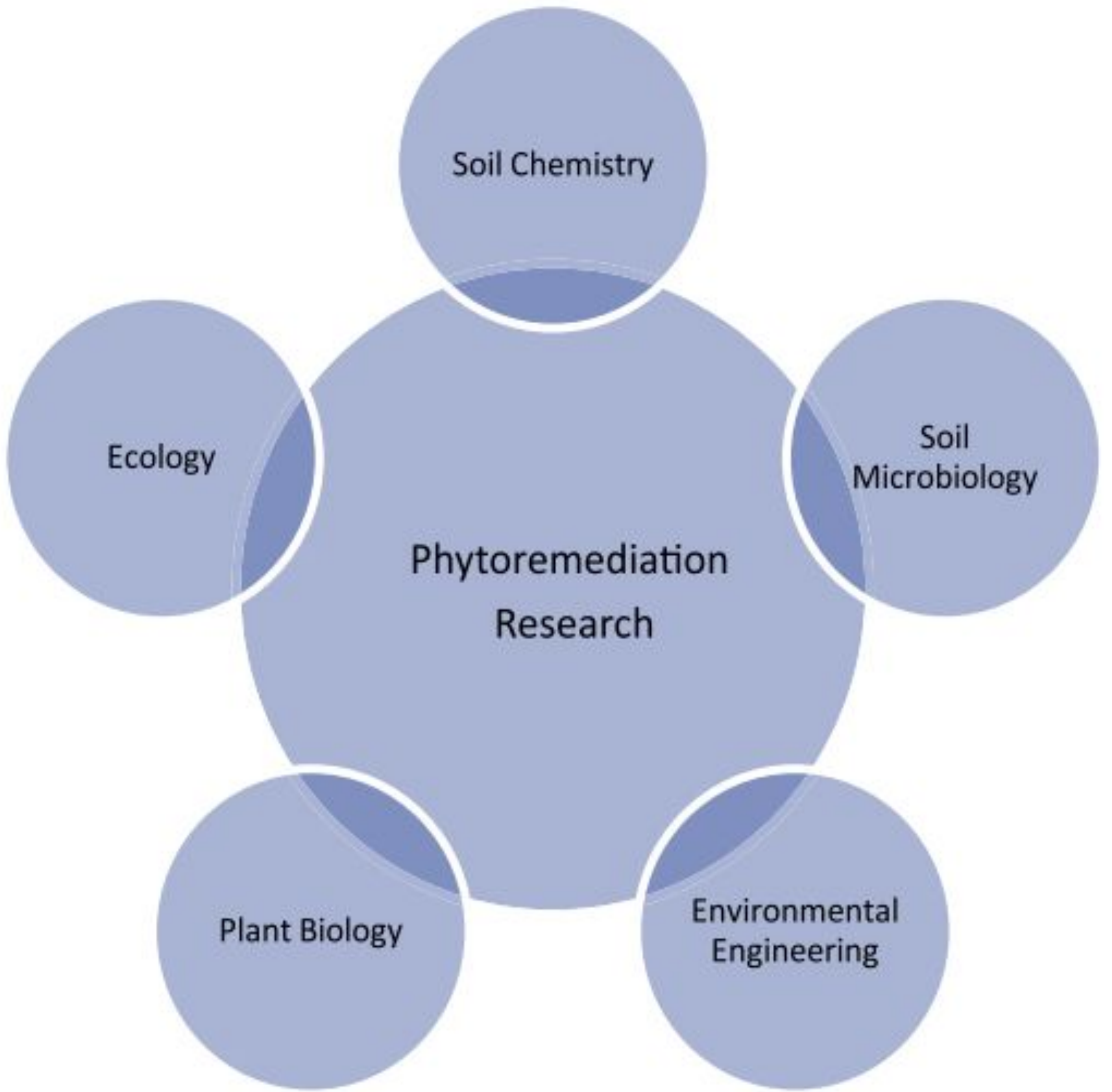


Fig. 3. Schematic showing interdisciplinary nature of phytoremediation research.

Conclusions

- Physical and chemical methods for clean-up and restoration of heavy metal-contaminated soils have serious limitations like high cost, irreversible changes in soil properties, destruction of native soil microflora and creation of secondary pollution problems.
- In contrast, phytoremediation is environment-friendly and ecologically responsible solar-driven technology with good public acceptance.
- ***phytomining*** – *a plant-based eco-friendly mining of metals, which can be used for extraction of metals even from low-grade ores*.
- Phytoextraction of heavy metals is expected to be a commercially viable technology for phytoremediation and phytomining of heavy metals in future.

Recommendations

1. Since phytoremediation research is truly interdisciplinary in nature, therefore researchers from different backgrounds should be welcomed and encouraged to utilize their talent and expertise in this field.
2. Existing plant diversity should be explored for hyperaccumulation of various heavy metals to find new effective metal hyperaccumulators.
3. Extensive and reliable risk assessment studies should be conducted before application of ***transgenic plants*** for phytoremediation in the field.
4. More phytoremediation studies should be conducted in the field with honest and unbiased cost-benefit analysis keeping in mind the very green nature of the technology.
5. More studies should be conducted to better understand interactions among the four players in the rhizosphere that is among ***metals, soil, microbes and plant roots.***
6. Advancement in spectroscopic and chromatographic techniques should be exploited to improve understanding of the fate of metal ions in plant tissues, which in turn will improve understanding of metal hyperaccumulation and tolerance in plants.