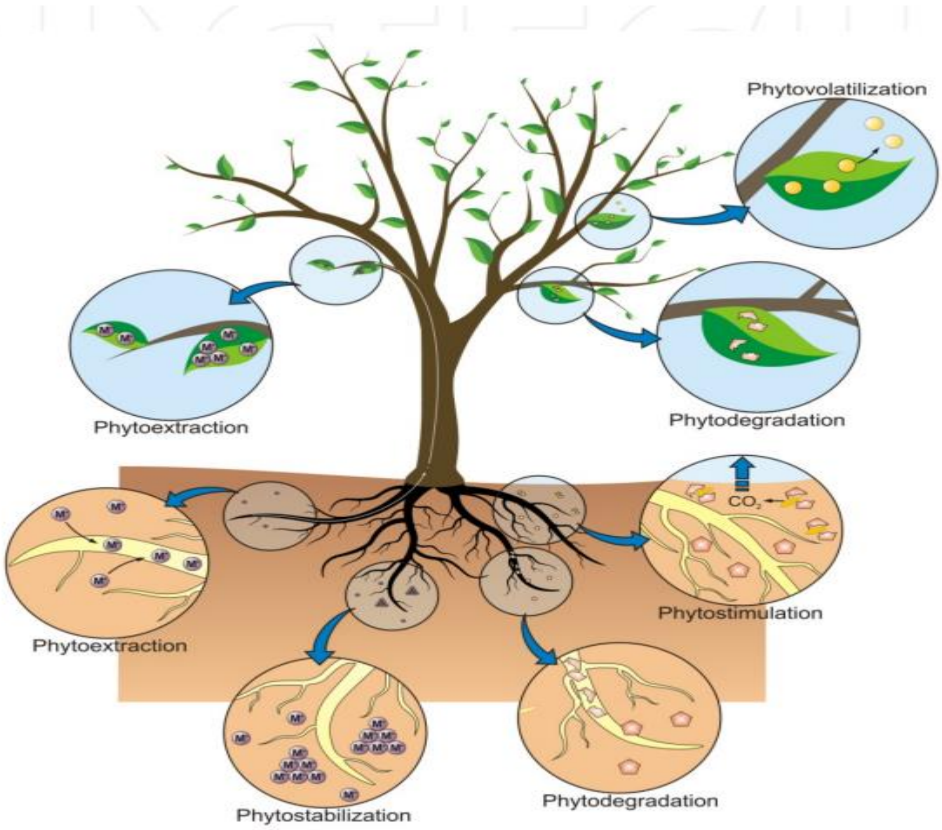


Development of Searchable Database for Phytoremediation for Plant Selection

Increasing the accessibility of existing data from field pilot trials

ROBERT B. MENSON

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

MASTER'S THESIS ACEX30

Development of Searchable Database for Phytoremediation for Plant Selection

Increasing the accessibility of existing data from field pilot trials

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ROBERT B. MENSON

Department of Architecture and Civil Engineering
DIVISION OF GEOLOGY AND GEOTECHNICS
RESEARCH GROUP ENGINEERING GEOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2023

Development of Searchable Database for Phytoremediation for Plant Selection
Increasing the accessibility of existing data from field pilot trials

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ROBERT B. MENSON

Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2023

Department of Architecture and Civil Engineering
DIVISION OF GEOLOGY AND GEOTECHNICS
ENGINEERING GEOLOGY
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover: The picture on the cover page shows phytoremediation technologies and associated processes and was extracted from section 1.1 of this report.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2023

Development of Searchable Database for Plant Selection for Phytoremediation

Increasing the accessibility of existing data from field pilot trials

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ROBERT B. MENSON

Department of Architecture and Civil Engineering
DIVISION OF GEOLOGY AND GEOTECHNICS
ENGINEERING GEOLOGY
Chalmers University of Technology

ABSTRACT

Environmental contamination is a global concern today and the level of contamination continues to grow due to rapid population growth, increased industrialization, aggressive agricultural practices, and other anthropogenic activities. There are several conventional methods which involve physical and chemical processes such as excavation, soil washing, chemical oxidation, thermal treatment etc. These conventional methods require the use of energy and heavy equipment which make them to be expensive and unstainable. Phytoremediation, the use of plants to remediate contaminated sites, presents promising potentials such as being eco-friendly and cost-effective, especially with sites of low or moderate contamination, though more research is required to investigate and support the evidence of its benefits. Despite its promising potentials, the practice of phytoremediation has received less attention, probably due to lack of knowledge of its efficiency. The choice of plants used in phytoremediation is, among other factors, an important aspect in planning and implementing phytoremediation projects. In this master thesis, data from various pot and field studies about the potential of different plant species, were gathered and used to develop a searchable database. The database is intended to facilitate plant selection and serve as a guide to practitioners, researchers, and other non-practitioners in planning an efficient and effective phytoremediation project. In addition to data obtained from literature review, a survey was conducted among stakeholders and experts in Sweden to incorporate their inputs in the development of the database. The data collected from various studies indicate that there are more studies on phytoremediation in Europe and North America. The literature review also showed that most of the studies are being reported in scientific articles. The database is projected to subsequently serve as a national repository of phytoremediation data for Sweden.

Key words: Phytoremediation, Searchable database, Pot and field studies, Plant selection, Contaminants, conventional methods

Contents

Preface

This master thesis is in fulfilment of the requirements of the Master Program in Infrastructure and Environmental Engineering at the Architecture and Civil Engineering Department. In this master thesis, literature review was used to collect data from existing and published pot and field studies about plant species potential in phytoremediation. The data were compiled and used to develop a searchable database which will facilitate plants selection when planning phytoremediation projects. A survey was conducted among stakeholders / experts in Sweden to get their input in the development of the database.

A huge thanks and appreciation to my supervisors, Jenny Norrman and Paul Drenning for their support and guidance throughout this project. Jenny Norrman was always ready to render support and answer questions via emails, texts and even phone calls, for this I am extremely grateful. Most of the data included into the database was previously compiled by Paul Drenning and I am thankful for this massive contribution. Sincere gratitude goes to my examiner, Lars Rosen for his tireless effort in providing me with feedback.

To the contaminated sites experts and researchers who provided me with their input during this project, words are inadequate to express how grateful I am.

It is worth to mention the tutorials provided by Sifa-Tool (an excel consulting company) for which the development of the database was possible on excel spreadsheet.

Finally, and most importantly, let me recognize the financial support of the Swedish Institute for a fully funded scholarship. Thank you for making me to realize my dreams! To my family, thank you for the prayers and for believing in me.

Göteborg March 2023

Robert B. Menson

1 Introduction

1.1 Background

The Contamination of the environment including soil, surface water, and groundwater is increasing due to exponential population growth, rapid industrialization, unsustainable agriculture practices etc. This results into disposal of waste (controlled or uncontrolled), spillage of contaminants, sewage sludge application for agricultural processes, mining and smelting of metal or metalloids (Sharma & Pathak, 2014). For this reason, there have been growing environmental concerns in terms of its sustainability. Both organic and inorganic compounds contaminate the environment; these contaminants include heavy metal, explosives, xenobiotic compounds, petroleum products etc. (Nikolić & Stevović, 2015). When the environment becomes contaminated, it must be remediated in a way that does not impose further environmental threat to the already injured environment. There are several remediation options (herein referred to as "conventional methods") which use physical, chemical, and biological processes to remediate contaminated sites. Research has shown that these conventional methods require high energy input, high cost and undermine the sustainable status of the sites being remediated. Gentle remediation options (GRO) have been identified as an alternative to conventional methods (especially where the site has a low or moderate contamination level) because of their potentials to remain environmentally friendly during remediation processes. Gentle remediation option (GRO) is defined as risk management strategies/technologies that result in a net gain (or at least no gross reduction) in soil function as well as risk management (A. Cundy et al., 2015).

Phytoremediation is a subset of gentle remediation options (GRO). In addition to phytoremediation (the use of plants), GRO also include the use of fungi (mcyco-remediation) and / or the use of bacteria-based methods, such as bioremediation, with or without chemical additives or soil amendments (A. Cundy et al., 2015). Phytoremediation is the use of green plant-based systems to remediate contaminated soils, sediments, and water (Cunningham et al., 1996). Compared to existing conventional methods, phytoremediation has been perceived to be cost-effective and environmentally friendly, though its application is limited to low or moderate contamination and shallow groundwater. Phytoremediation uses technologies such as phytostabilization, rhizofiltration, rhizodegradation, phytoextraction, phytodegradation, phytovolatilization and hydraulic control (Sharma & Pathak, 2014); these technologies are demonstrated in Figure 1-1. The remediation of contaminants by phytoremediation depends on the type of mechanism being used. These mechanisms include 1) extraction of contaminants from the media and their concentration within the plants tissue 2) degradation of contaminants by biotic or abiotic processes 3) volatilization or transpiration of volatile contaminants from plants to air 4) hydraulic control of contaminated water (plume control) and 5) vegetative cover (Sharma & Pathak, 2014). Phytoremediation targets contaminants such as metals, metalloids, petroleum hydrocarbons, pesticides, explosives, and chlorinated solvents (Cunningham et al., 1996). Selection of a particular phyto-technology depends on the objective of the remediation and the type of contaminants that are targeted in the remediation project. For example, a site contaminated with metals can suitably be remediated using technologies such as phytoextraction, phyto-stabilization, and rhizofiltration (Salt et al., 1995) while organic contaminants can be remediated using technologies such as phytodegradation, rhizo-degradation, phytovolatilization, etc. (Drenning, 2021). Since the inception of phytoremediation, there have been several experiments including pot and field experiments (Arthur et al., 2005; Cook & Hesterberg, 2013; Cunningham et al., 1996; Gerhardt et al., 2017; Jacklin et al., 2021; Salt et al., 1995; Sharma & Pathak, 2014) to study the ability of different plants species. Despite that research has clearly shown that, under several conditions, phytoremediation can be applied quite effectively in contaminated sites (Gerhardt et al., 2017), its use has been underutilized and this is true in Sweden (Chang & Hogland, 2022) and elsewhere in the world (Gerhardt et al., 2017). This underutilization may be due to several reasons ranging from the limited number of plants with the potentials to work effectively in phytoremediation to the inadequate abilities of native plants to remove contaminants (Arthur et al., 2005). Another aspects that limit the use of phytoremediation according to Drenning, (2021), include the status quo bias and preference of conventional methods such as dig-and-dump by practitioners, lack of knowledge by practitioners about their functionalities, and methods in handling uncertainties and limitations.

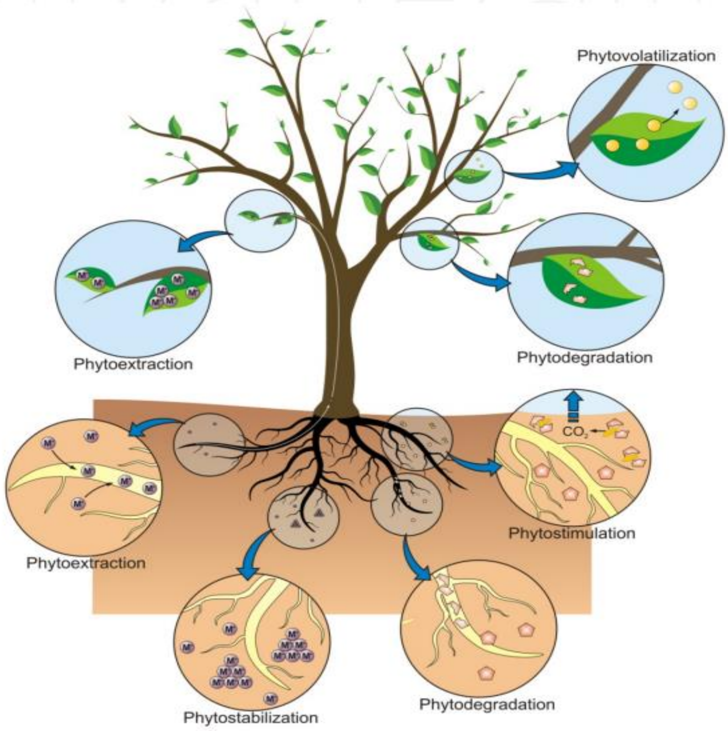


Figure 1-1: Schematic representation of phytoremediation strategies. Source: (Favas et al., 2014).

To expand the viability and increase the use of phytoremediation technologies in contaminated sites remediation, the existing knowledge gap should be shortened while encouraging practitioners to adapt the use of these technologies. Since phytoremediation technologies use plants to treat contaminants, good knowledge of how plants treat contaminants as well as the interactions between the contaminants, the plants, and micro-organisms is crucial to the selection of pant species which determines the success and efficacy of phytoremediation (Kafle et al., 2022). In plant selection, some key criteria are considered. For example, when selecting plants for phytoextraction, criteria such as production of above-ground biomass, high rate of heavy metal accumulation from the soil, translocation of accumulated heavy metal from roots to shoots, tolerance of toxicity from the accumulated heavy metal, resistance to pathogens and pests etc. are considered (Drenning, 2021). Several research works (Arthur et al., 2005; Cook & Hesterberg, 2013; Cunningham et al., 1996; Gerhardt et al., 2017; Jacklin et al., 2021; Salt et al., 1995; Sharma & Pathak, 2014) have emphasized the importance of plants selection to the success of phytoremediation projects. In addition, knowledge of factors that influence phytoremediation technologies plays a pivotal role in the success of any phytoremediation technologies. For example, different plants work well with different soils and climatic conditions. Phytoremediation technology successfully used in remediating a particular contaminant under certain site conditions cannot be extrapolated to other contaminated sites (Suresh & Ravishankar, 2004).

Planning a phytoremediation project is challenging because its efficiency depends on many factors, thus requires extensive research and trial studies. The choice of plants is a major component in the planning and designing of phytoremediation projects. Research has found several plant species with suitable characteristics and potential to remediate contaminated sites, unfortunately, the results from these studies have been published in format such as books, and scientific journals which reduce their accessibility by practitioners (Famulari & Witz, 2015). Even if these studies have been reported digitally, the volume of the data is too huge that browsing through to gather needed information is not practical. As a result, the practice of phytoremediation continues to face challenges. If these study results are reported in a searchable database instead, it will provide opportunities for practitioners who are interested in the results to have easy access. A phytoremediation database containing data from existing and published studies will save time and money for new studies.

Given the above explanations, it is important to develop methods of increasing the accessibility of study results and knowledge about the strengths of phytoremediation. One of such methods is the development of a searchable database containing data from existing and published pot and field studies on plants performance in phytoremediation. This will create opportunities for practitioners who are interested to explore the possibilities of phytoremediation application in their projects. With this, it is easy for practitioners working with contaminated sites to explore the possibility of applying phytoremediation in the remediation of contaminated sites.

1.2 Aims and Objectives

The overall aim of this master thesis is to catalogue suitable data to facilitate plant selection for practitioners in phytoremediation projects by developing a searchable database containing data from existing and published pot and field studies on the potential of plant species in phytoremediation.

To achieve the aim, the following specific objectives are identified:

- **i.** Conduct literature review to gather available and suitable data (from pilot and field studies) to be included into the database.
- **ii.** Conduct survey among practitioners to complement data from pilot and field studies.
- **iii.** Classify the different phytoremediation technologies.
- **iv.** Development a searchable database using appropriate freeware.

1.3 Research Questions

In fulfilment of the aims and objectives of this master thesis, the following research questions were formulated:

i. Which data are relevant to include in the database?
ii. Which variables can be searchable to support practitioners?
iii. What additional data can be obtained from practitioners / stakeholders to support the development of the database?
iv. How can a searchable database support practitioners?
v. What are the different phytoremediation technologies and their associated processes?
vi. What type of freeware is suitable to develop the database?
vii. What other data are available in scientific databases that can be included in such a database?

1.4 Scope and Limitations

1.4.1 Scope

This master thesis project under the title "Development of Searchable Database for Phytoremediation for Plants Selection" is conducted in fulfilment of the requirement for the Master Program in Infrastructure and Environmental Engineering at Chalmers University of Technology. It covers the background and overview of phytoremediation and the advances that are being made in promoting its application. The technologies, mechanisms, strength and limitations and cost of phytoremediation are discussed. To facilitate the database development, existing databases were explored to have an idea of the type of data to include. Experts and stakeholders' inputs were considered in the development of the searchable database through survey and workshop. The database was built on a an excel spreadsheet and contains data from existing and published pot and field studies from Europe, North America, Asia, Australia, South America, and Africa.

1.4.2 Limitations

While this report contains useful information about phytoremediation and its application, it is necessary to note some limitations as outlined below:

- The data contained in the database are only from scientific articles and do not include other types of reports.

- The database is developed using an excel spreadsheet which is not completely free. Users need to have Microsoft 365 subscription to have access.

- Only 19% of data included in the database is pot studies. This means that users who may want to use the database for planning a pot study will be presented with limited data.

2 Theory

2.1 Brief History of Phytoremediation

Phytoremediation is the use of plants to clean up contaminated land (Ghaly et al., 2005). Phytoremediation cleans up contaminated land using physical, chemical, and biological interactions between the plants and the media (i.e., soil, water, sediment, and air) (Nagendran et al., 2006). The use of plants to remediate contaminated sites is as old as 300 years ('Tonelli et al., 2022). The interest to study the interaction between plants and contaminants, specifically plant species tolerant to heavy metal can be dated as far back as the 16 century (Stephenson & Black, 2014) though environmental pollution was of less concern ('Tonelli et al., 2022). From 1750, the concern for the environment started to be noticed in Europe. The first industrial revolution, though improved economy, and lifestyle, but also came with changed consumption habits and means of transport (Mohajan, 2019). Coal burning in the British industries negatively impacted the cities and people as well as the health of the employees of those industries (Thank et al., 1913). From 1860 to 1914, the second industrial revolution, (mainly affected the United States) gave rise to more economical benefits such as improvement of electricity, internal combustion engine etc., but also created more environmental pollution sources ('Tonelli et al., 2022). During this same period, reduction of biodiversity started to get noticed while the use of pesticides and other aggressive fertilizers started to get into practice (Mohajan, 2020). The first World War, which ended in 1918 created more environmental problems when forests were converted into vegetal area containing trenches and roads which ended up with heavy metal and explosive contamination (Heiderscheidt, 2018). In 1930s, research was already advancing when it was discovered that some plants which are grown in the presence of persistent contaminants such as selenium, could be used to uptake these contaminants at high level (Beath & Gilbert, 1937). The nuclear attacks of the second World War created even greater environmental pollution thus making it more cumbersome for human beings to handle ('Tonelli et al., 2022). During the 1940s and 1950s, more studies were being developed to understand the impact of pollution on plants and in 1944 scientists observed damages to some plant's leaves induced by polluted air (smog) (Haagen-Smit et al., 1952). In 1960s, scientists were able to determine Fe, Cu, Mn, and Zn in vegetal samples using ion exchange and spectrophotometric methods ('Tonelli et al., 2022). The study of pollutants removal by plants continued in the 1970s when scientists discovered that some plant species are able to remove more than one pollutant from the environment, for example, aeolanthus biformifolius demonstrated the ability to perfectly remediate contaminated sites by accumulating high levels of both Cu and Co ('Tonelli et al., 2022).

As study of plants ability to remediate contaminated areas continues, in late 1970s, researchers discovered more and more plant species such as the Sebertia acuminate which could accumulate nickel (Jain et al., 1989) and began to identify procedures by which plants could remediate contaminated sites. The use of plants to uptake contaminants was not called phytoremediation from the beginning, though plants were being used to remediate pollutants such as PCB and landfill leachates (Gómez-Gutiérrez et al., 2007; Jones et al., 2006). The term *hyperaccumulator* was first used when researchers discovered that some plants could accumulate very high amounts of heavy metals while dealing with the stress induced by the pollutants (Brooks et al., 1977). The term phytoremediation was then invented, and it is a combination of a Greek word -*phyto* and Latin word- *remedium* which mean "*plant*" and "*restore*" respectively (Cunningham et al., 1996).

Phytoremediation uses several technologies which are being studied to understand how each of them work. How and when each of these technologies is applied depend on factors such as the type of contaminant, site-specific conditions, such as soil type and depth of groundwater table from the surface, cost, and end use of the land (Chirakkara et al., 2016). According to Miller (1996), these techniques are still being tested in lab and field scale studies. Current research about phytoremediation technologies includes 1) lab studies to investigate the processes behind phytoremediation; 2) screening studies to find suitable plants for further investigation; 3) bench- and pilot-scale testing of promising plant species; and 4) limited and full-scale field trials (Miller, 1996). When Mendez & Maier (2008) studied phytoremediation of mine tailings in temperate and arid environments, they found out that phytoextraction and phytostabilization are two main approaches used to remediate mine tailings. According to the study, phytoextraction is limited because of its low rates of metal removal which is a combination of low biomass production and insufficiently high metal uptake into plant tissue while phytostabilization is currently limited by a lack of knowledge of the minimum amendments required (e.g., compost, fertilizer) to support long-term plant establishment (Mendez & Maier, 2008). There have also been several studies on plants used in phytoremediation. According to Suresh & Ravishankar (2004), plants function in phytoremediation in two ways which include the facilitation of favorable conditions for microbial degradation, specifically by plant root colonizing microbes, and plant root itself by providing a simple and inexpensive means of accessing contaminants that exist in subsurface soils and water. Grasses are more suited for the remediation of heavy metal because of their growth habitat and adaptability to a wide range of edaphic and climatic conditions (Singh et al., 2003). In their research about the overview of metallic ion decontamination from soil using phytoremediation, Singh et al. (2003) found out that metal-hyperaccumulating plants, desirable for heavily polluted environments, can be developed by the introduction of novel traits into high biomass plants in a transgenic approach. In this promising strategy, the genetic manipulation of a phytoremediator plant needs several optimization processes, including mobilization of trace elements/ metal ions, their uptake into the root, stem and other viable parts of the plant and their detoxification and allocation within the plant (Singh et al., 2003). In assessing tropical grasses and legumes for phytoremediation of petroleum contaminated soil, Merkl et al. (2005) experimented with three legumes (*Calopogonium mucunoides,Centrosema brasilianum, Stylosanthes capitata*) and three grasses (*Brachiaria brizantha, Cyperus aggregatus, Eleusine indica*) to test for their ability to stimulate microbial degradation in soil contaminated with 5% (w/w) of a heavy crude oil. After six weeks, the legumes died while the grasses exhibited reduced biomass production under the influence of contaminants (Merkl et al., 2005). The death of the studied legumes, according to the studies, is an indication of limited potential of short-term greenhouse screening experiments for the evaluation of plant species for phytoremediation.

2.2 Phytoextraction

Phytoextraction is a common technology used in phytoremediation and refers to the ability of plants to uptake inorganic contaminants (Arthur et al., 2005). As the name suggests, this technology uses the mechanism of extraction which removes the source of the contaminants. Phytoextraction functions as “bio-pumps” to take up contaminants from the media (soil, sediments, and groundwater) and translocate them into the shoots, which can then be harvested (Mench et al., 2010; Robinson et al., 2003). Though the harvested plants / biomass must be disposed of in a sustainable way, but the disposal of the contaminant-rich biomass is considered as cost-effective compared to excavation and disposal of contaminated soil as done with conventional methods (Drenning, 2021). Phytoextraction process involves i) cultivating well selected plant species on the contaminated site, ii) harvesting and removal of biomass containing contaminants from the site and iii) post-harvest treatment of biomass through composting, landfilling or incineration (Mench et al., 2010; Robinson et al., 2003). Depending on prevailing conditions, post-harvest treatment may aim at reducing the volume and weight of the biomass for disposal as hazardous waste or for use to promote circularity by recycling to reclaim trace elements of economic values (Vangronsveld et al., 2009). Phytoextraction is mainly used to remediate soil, sediments and sludges contaminated with heavy metals and radionuclides (Sharma & Pathak, 2014). The approaches used in phytoextraction of trace elements include i) the use of hyperaccumulators for continuous or natural phytoextraction; ii) the use of fast-growing plants such as Salix or Populus Sp for continuous or natural phytoextraction; and iii) the use of amendments such as chelators for induced or chemically assisted phytoextraction (Mench et al., 2010; Vangronsveld et al., 2009). The concentration of trace elements in the shoots of the plants (which is determined by the bio-concentration factor) and the amount of biomass produced are two main determining factors of the maximum trace elements absorption (Keller et al., 2003).

2.2.1 Mechanism of Phytoextraction

The general mechanisms used by phytoextraction include absorption of metal cations which is followed by metal-phytochelatin complex (M-PC) or metal-ligand complex formation inside the plant cell (Asgari Lajayer et al., 2019). These mechanisms are performed by hyperaccumulating plants (referred to as hyperaccumulators). When naturally occurring plants are able to uptake, translocate and tolerate contaminants in the above-ground parts to the concentration of 0.1 to 1% in excess of the biomass produced, they are referred to as hyperaccumulating plants (Cunningham et al., 1996). Figure 2-1 demonstrates how phytoextraction works.

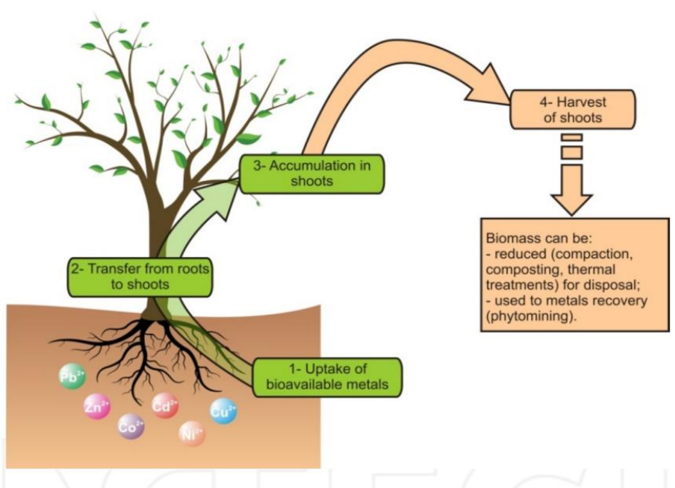


Figure 2-1: Schematic representation of phytoextraction of metals from soil. Source: (Favas et al., 2014)

2.2.2 Plants (Hyperaccumulators)

The choice of plants plays an important role in the success of phytoextraction because the plant selected must possess the hyperaccumulating characteristics to uptake and translocate metal. According to Li et al. (2010), the potential of plant species to extract metal is determined by plant biomass and concentration of the metal in the shoots. Example of plant species suited for phytoextraction include Sesbania drummondii (Barlow et al., 2000); ii) Pteris vittata (Salido et al., 2003); iii) Sedum alfredii (Zhou & Qiu, 2005); and iv) Commoelina communis (H. Wang et al., 2004) for the accumulation of Pb, As, Cd and Cu respectively. In addition to absorption and translocation of metal, candidate plant species in phytoextraction must be fast-growing and be able to produce large biomass. Some bacteria are used to stimulate plant growth for optimizing phytoextraction. Example of bacteria that promote plant growth include i) *Stenotrophomonas maltophilia* and ii) *Agrobacterium s*p (Guarino et al., 2020).

2.2.3 Strength of Phytoextraction

The advantages of phytoextraction includes (Kafle et al., 2022):

- Metal and radionuclide in chemical mobile forms are very harmful to human health, phytoextraction can trap and translocate these contaminants.
- Compared to conventional methods involving excavation, phytoextraction is cost-effective and sustainable.
- Phytoextraction leaves the soil fertile, thereby promoting the growth of vegetation.

2.2.4 Limitations of Phytoextraction

Despites the merits of phytoextraction, there are some limitations (Kafle et al., 2022):

- Phytoextraction takes a longer time to reach remediation goals.
- The application of phytoextraction to wetlands is limited.
- Plants used in phytoextraction will have to be harvested and safely disposed of
- Accumulation of metal into the shoots may pose threat to animals that eat the plants.

2.3 Phytostabilization

Phytostabilization involves restricting the movement of contaminants (immobilization). Phytostabilization can be defined as i) the ability of plants to immobilize contaminants in soil through absorption and accumulation by roots, adsorption onto the roots, precipitation into the roots zone, or by physically stabilizing the soil in a way that restricts or reduces the transport of the contaminants through food chain, permeation to groundwater, and re-entrainment or resuspension (A. B. Cundy et al., 2016; Mench et al., 2010; Vangronsveld et al., 2009); and ii) the use of plants and roots to prevent the movement of contaminants through wind, erosion, leaching, and dispersion (Sharma & Pathak, 2014). Phytostabilization can immobilize or inactivate contaminants in and around the root zones, sometimes with the use of different soil amendments (Mench et al., 2010; Vangronsveld et al., 2009). This technology was introduced as an alternative to phytoextraction which presented some limitations such as long duration (decades) to reach remediation goals (Gerhardt et al., 2017; Mench et al., 2010; Vangronsveld et al., 2009). Contaminants removal from the site is not always possible or may be difficult depending on the site characteristics / or cost of removal, in this case phytostabilization is an appropriate alternative, where the intrinsic risk of the contaminants is reduced (Arthur et al., 2005).

2.3.1 Mechanisms of Phytostabilization

Remediation by phytostabilization involves processes such as adsorption, absorption and accumulation into the roots, precipitation, complexation, and metal valence reduction (Sharma & Pathak, 2014). In phytostabilization, contaminants mobility and bioavailability are reduced due to the stabilizing processes by the plant roots, thereby reducing the toxicity of the contaminants. In other cases, the contaminants are not further available in toxic form or their release from the solid matrix after being accumulated is prevented (Kafle et al., 2022). As an example, herbicide trifluralin can be transformed into less harmful substance (bound residue) by Ryegrass (Kafle et al., 2022). Contaminants are immobilized within the rhizosphere (roots zone) of the plants by help of photochemical exudates or sometimes the contaminants are entrapped into the root surface by transported protein, yet phytostabilization can be achieved by sequestering contaminants inside the vacuole of root cells by cellular processes (ITRC Phytotechnologies Team, 2009). In Figure 2-2, the concept of phytostabilization is depicted.

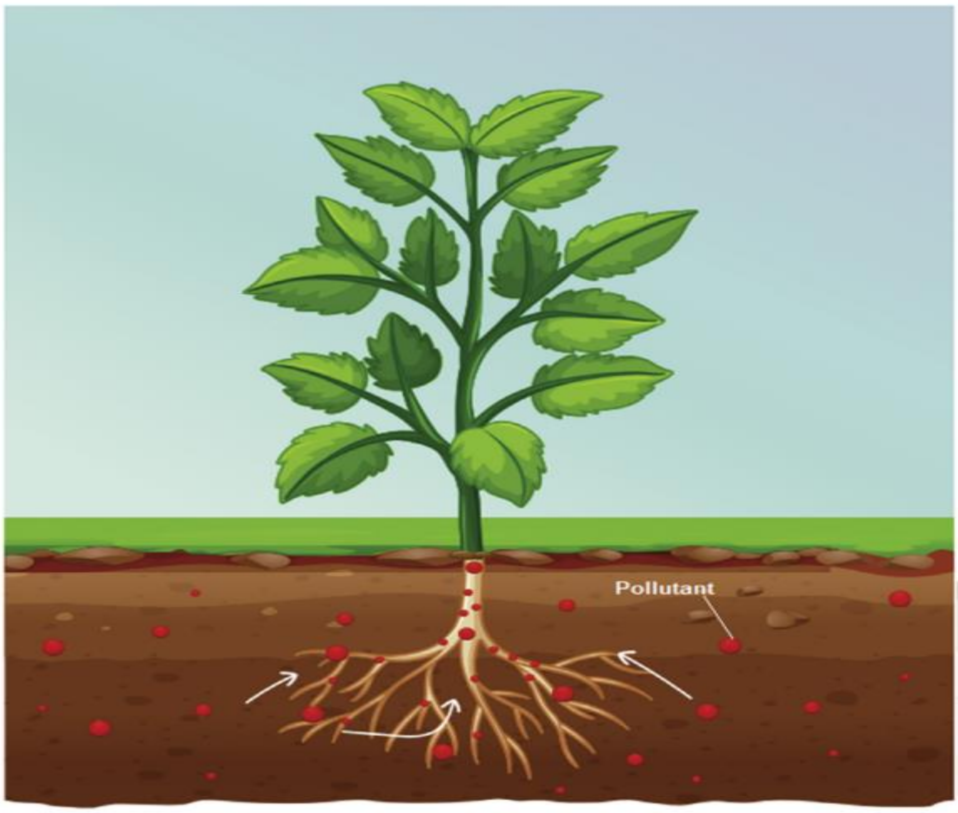


Figure 2-2: General mechanisms of phytostabilization of heavy metals. Source: (Tonelli et al., 2022).

2.3.2 Plants Used in Phytostabilization

To achieve remediation goals, plants selected for phytostabilization must possess some qualities such as tolerant to metals, production of large amount of biomass, translocation of negligible amount of contaminants / metals to the shoots, must be noninvasive or native of the site, and must have a wide-range roots system (Alkorta et al., 2010), Plants selection is very cardinal to the success and efficiency of phytostabilization because how much metal is absorbed depends greatly on the type of plant species used. Plants species of the same genus and clonal can take up metal at different levels (Mench et al., 2010; Vangronsveld et al., 2009), so when selecting plant species for phytostabilization, it is recommended to carefully consider the characteristics.

2.3.3 Strength of Phytostabilization

Phytostabilization has several advantages as outlined below (Kafle et al., 2022):

- Phytostabilization restricts the movement of contaminants without needing to remove them from their location (in situ treatment)
- Improves soil fertility and may enhance ecosystem restoration.
- It is an in-situ technology and does not require disposal of waste from treatment.

2.3.4 Limitations of Phytostabilization

The demerits of phytostabilization include the following (Kafle et al., 2022):

- Plants used in phytostabilization may require the use of fertilizers or other amendments to enhance remediation.
- Does not reduce the total concentration of contaminants, instead makes them less mobile and less bioavailable thereby reducing potential risk (risk-free site but not contaminant-free site)
- Contaminants are not destroyed therefore plants restricting contaminants movement need continuous maintenance to prevent re-release.
- In case of solubility cause by roots exudates and amendments, contaminants leaching may result.
- Since the aim is to contain the contaminants, translocation must be avoided.

2.4 Rhizofiltration

Rhizofiltration initially performs like phytostabilization since it works through adsorption and absorption of contaminants. It is a technique in which plant roots remove contaminants from saturated zones to remediate aqueous contaminants from media such as wastewater, abstracted groundwater or surface water through adsorption, absorption, precipitation or accumulation onto plant roots or other submerged parts of metal-tolerant aquatic plants (Jadia & Fulekar, 2009). The duration to reach remediation goal depends on the type of vegetation used. According to A. B. Cundy et al. (2016), rhizofiltration can reduce the concentration of contaminants in water outflow within 1 to 2 years, when used as part of phytomanagement. This technology is especially effective and economical with low contaminants concentrations and with large volume of water in the contaminated site; a reason for which it is applicable for the remediation of radionuclide contaminated water (Salt et al., 1995). Typical contaminants for which rhizofiltration is recommended include metals such as lead, cadmium, cooper, nickel, zinc, chromium etc. and radionuclides such as uranium, cesium, and strontium (Sharma & Pathak, 2014).

2.4.1 Mechanisms of Rhizofiltration

During the rhizofiltration process, contaminants are immobilized or accumulated onto or within the plant roots after which the contaminants are removed from the media through the physical removal of the plant (Sharma & Pathak, 2014). Depending on which contaminants are being remediated, plants may uptake, and concentrate (Kafle et al., 2022; Sharma & Pathak, 2014). The mechanisms involved in rhizofiltration greatly depends on the physical and biochemical impacts of the plant roots within the media being remediated which are further dependent on the efficiency of the plant roots to synthesize certain chemicals causing the contaminants to be accumulated in the plants body (Fulekar & Pathak, 2012). Figure 2-3 describes the mechanism of rhizofiltration.

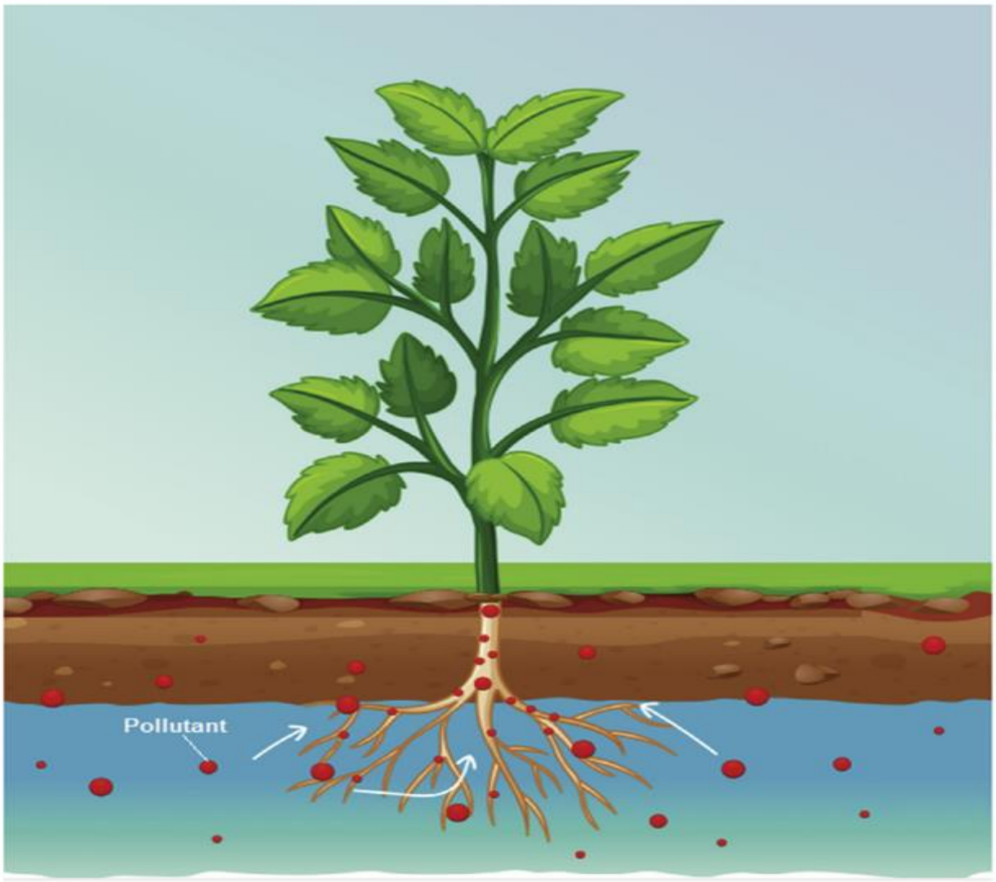


Figure 2-3: Rhizofiltration and its mechanism. Source:(Tonelli et al., 2022).

2.4.2 Plants Used in Rhizofiltration

Though both terrestrial and aquatic plants can be used in rhizofiltration but when comparing the two, terrestrial plants are desirable because of their possession of more developed root and fibrous systems which provides a large surface area for a better absorption (Cristaldi et al., 2017). It is recommended to consider certain factors when selecting plants for rhizofiltration; such factors include hypoxia-tolerant, metal-tolerant, and large surface area for absorption (Cristaldi et al., 2017; Zhang et al., 2009). Another major aspect to consider during plant selection is to ensure that plants used in rhizofiltration are not efficient translocators of metal and this is because metal transport to the shoot makes rhizofiltration less efficient by producing more contaminated plant residue (Salt et al., 1995). The plants used in rhizofiltration are usually grown in a greenhouse where their roots are suspended (hydroponic) in water. When the root system is sufficiently developed, their source water is substituted with contaminated water for plants acclimatization; this is then followed by planting the plants in the contaminated sites where they are used to absorb the water along with the contaminants (Fulekar & Pathak, 2012; Ya & Ramachandra, 2006). Examples of suitable plants used in rhizofiltration include *Salix spp, Populus spp, Brassica sp., Phragmites australis (or common reed) and Typha spp. (reed, cattail) which are used in site such as constructed wetlands* (Cristaldi et al., 2017; Drenning, 2021).

2.4.3 Strength of Rhizofiltration

Rhizofiltration technology has many advantages which include the following (Farraji et al., 2016):

- Can be used for both in-situ (i.e., the use of floating rafts on ponds) and ex-situ (i.e., the use of a well-engineered tank for abstracted groundwater or wastewater) remediation program.
- The ex-situ remediation system can be setup in any location.
- It is well suited for the remediation of heavy metal and radioactive elements.

2.4.4 Limitations of Rhizofiltration

Limitations of rhizofiltration technology can be summarized as (Farraji et al., 2016):

- Requires skills to design the system so that influent concentration and outflow rate are well controlled.
- The plants used must be grown in greenhouse and then transplanted.
- Routine harvesting and disposal of plants is required to remove contaminants.
- The pH of the source water must be adjusted from time to time to ensure efficiency.

2.5 Phytodegradation

When a compound is broken down from its original toxic form into smaller constituents, less harmful form, or into a metabolite, it is said to be degraded (Kafle et al., 2022). The use of plants to take up and breakdown (degrade) organic contaminants in the soil through microbial activities is referred to as phytodegradation (Arthur et al., 2005). Phytodegradation can also mean the breakdown of contaminants external to the plants through enzymes excreted by plants or microorganism (Stolberg & Zadniprovska, 2007). The enzymes involve in phytodegradation include i) dehalogenase (transformation of chlorinated compounds); ii) peroxidase (transformation of phenolic compounds); iii) nitroreductase (transformation of explosives and other nitrate compounds); iv) nitrilase (transformation of cyanated aromatic compounds); and v) phosphatase (transformation of organophosphate pesticides) (Deng & Cao, 2017; Susarla et al., 2002; Winquist et al., 2014).

Phytodegradation is suited for the remediation of sites contaminated with organic contaminants such as herbicides, chlorinated solvents, and PAHs (Yin et al., 2011) as well as for the recovery of groundwater and surface water. Though phytodegradation can be used to remediate contaminated surface water, but its application is mainly recommended for contaminated soil, sludges, sediments, and groundwater (Kafle et al., 2022). Main targeted contaminants in phytodegradation are organic compounds though it is also used to treat inorganics nutrients such as nitrates which are taken up by plants and converted in nitrogen and proteins (Dec & Bollag, 1994).

2.5.1 Mechanisms of Phytodegradation

The key mechanisms utilized by phytodegradation are plant uptake of contaminants and metabolic processes. Plants can take up contaminants and store them into their tissues, the enzymes within the plants can then work to transform the contaminants into molecules that can be degraded or release into the plant's exudates (Arthur et al., 2005). The bioavailability of contaminants determines the efficiency of phytodegradation. The bioavailability of a contaminant is determined by its hydrophobicity, for example $logK_{ow}$ of 0.5 – 3.5 (Drenning, 2021). The uptake of organic contaminants by plants depends on several factors such as the type of plants used, the type and age of the contaminants, the physical and chemical characteristics of the soil etc. (Sharma & Pathak, 2014). The procedure of phytodegradation is demonstrated in Figure 2-4.

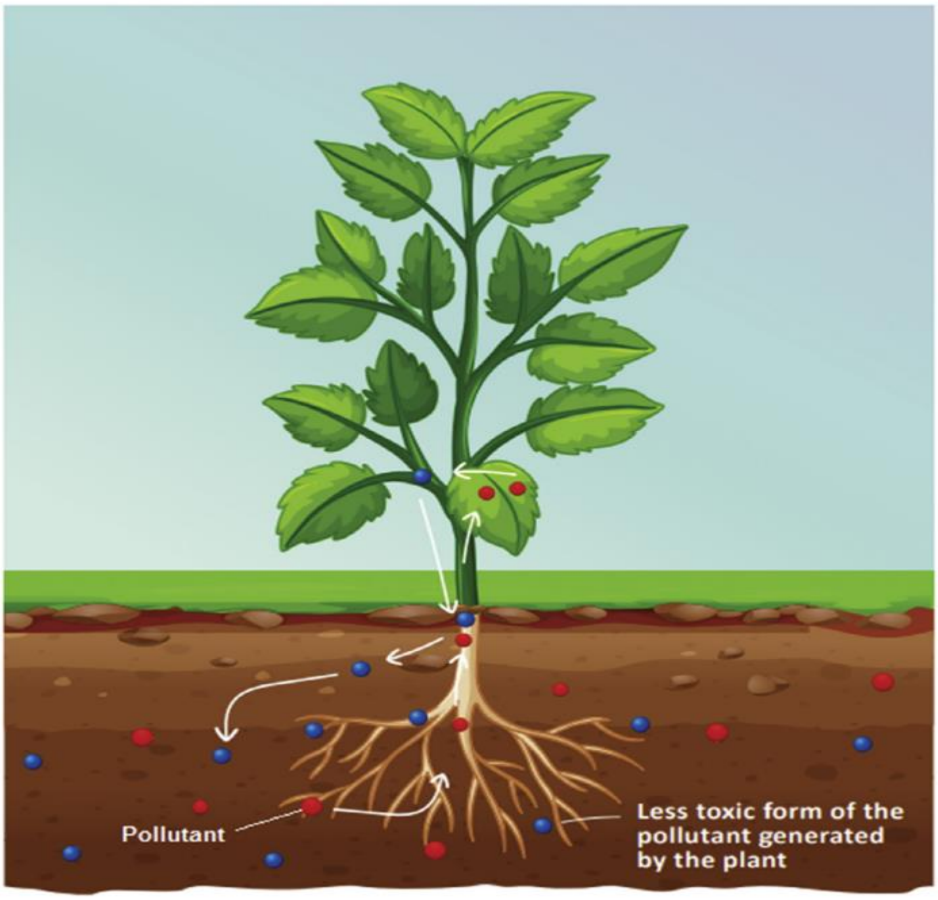


Figure 2-4: Phytoremediation through phytodegradation mechanism. Source: (Tonelli et al., 2022).

2.5.2 Plants Used in Phytodegradation

Different types of plants have been used in phytodegradation and are listed in (Gutiérrez-Ginés et al., 2014). Plant's role in phytodegradation can be directly or indirectly. As a direct role, the contaminants are absorbed and broken down by the plants into less harmful compounds which are then distributed within the plant tissues (Kafle et al., 2022). In the indirect case, the degradation happens within the rhizosphere (root zone) of the plants, in this case, the technique is referred as rhizodegradation (which is discussed in section ***2.6*** of this report). For example, plant species such as *Tegetes patula*, *Ipomea balsamina*, and *Mirabilis jalapa* can dechlorinate chlorinated hydrocarbons and transform them into non-toxic chemicals, while the reductive dehalogenation of DDT was also observed in aquatic plant *Elodea* and terrestrial plant *Kudzu* (Garrison et al., 2000; Kafle et al., 2022).

2.5.3 Strength of Phytodegradation

The phytodegradation technology is advantageous because (Kafle et al., 2022):

- It can be used to remediate contaminated sites in-situ.
- Contaminants are transformed into less harmful substances, (i.e., dimethyl selenite gas.)
- As metabolites are released to the atmosphere, they may be exposed to natural degradation processes and further degrade.

2.5.4 Limitations of Phytodegradation

However, there are some drawbacks associated with the application of phytodegradation (Kafle et al., 2022):

- Contaminants or hazardous metabolites may be transpired into atmosphere during the process.
- Accumulation into vegetation (food chain) is possible which can then be taken up by eating the fruits.

2.6 Rhizodegradation

Rhizodegradation, like phytodegradation, involves the uptake and breakdown of organic contaminants but the degradation happens outside the plant as opposed to inside the plant tissue. It is a biological treatment of contaminants which is assisted by microbial activity happening within the rhizosphere of the plants (Susarla et al., 2002). Rhizodegradation can be referred to as plant-assisted degradation, plant-assisted bioremediation, plant-aided in-situ biodegradation, and enhanced rhizosphere biodegradation (Stolberg & Zadniprovska, 2007). The rhizosphere can be described as a zone of increased microbial density and activity at the root/surface where plants and microorganisms engage in symbiotic activities, making the rhizosphere an microbially active zone (Curl & Truelove, 1986). Rhizodegradation can be used to remediate a wide range of contaminants including total petroleum hydrocarbon (TPH), PAHs (polycyclic aromatic hydrocarbons), BTEX (Benzene, toluene, ethylbenzene, and xylenes), Chlorinated solvents (i.e., TCE, TCA), PCP (pentachlorophenol), Pesticides, PCBs (polychlorinated biphenyls), Surfactants (Aprill & Sims, 1990; Azadpour & Matthews, 1996; Narayanan et al., 1995; Sharma & Pathak, 2014).

2.6.1 Mechanisms of Rhizodegradation

Microorganisms such as fungi, yeast and bacteria are the main drivers for rhizodegradation (Ely & Smets, 2017; J. Wang et al., 2017). These microorganisms, which are found in the rhizosphere than the ground surface, excrete exudates containing amino acids, carbohydrates, and flavonoids during the process of rhizodegradation; these nutrients-rich exudates enhance the metabolic activities by providing oxygen and carbon dioxide sources within the rhizosphere for use by the microorganisms (Ali et al., 2013; Cristaldi et al., 2017). In addition to the enhancement of contaminants removal by the nutrients-rich rhizosphere, plants release enzymes which can help to stimulate the growth of soil microbes and the degradation of the organics in the soil (Ho-Man et al., 2013). Figure 2-5 displays process of rhizodegradation.

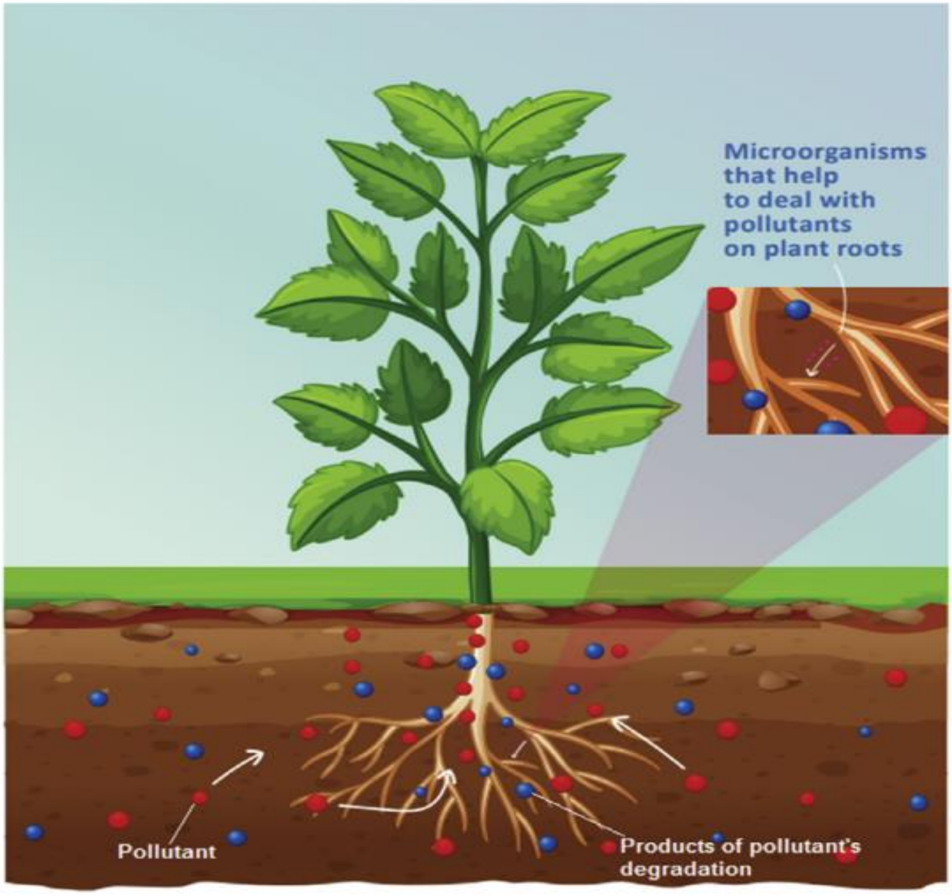


Figure 2-5: Phytoremediation through rhizodegradation. Source: (Tonelli et al., 2022).

2.6.2 Plants Used in Rhizodegradation

When selecting plants to be used in rhizodegradation, it is recommended to consider plants that have the ability to produce exudates that stimulate the growth of degrading microorganisms (Kafle et al., 2022). Different plant species produce exudates of varying composition and characteristics at different rates. Examples of plants that have exhibited good potentials for rhizodegradation are discussed in(Aprill & Sims, 1990; Azadpour & Matthews, 1996; Cunningham et al., 1996; Federle & Burney, 1989; Jordahl et al., 1997; Narayanan et al., 1995) and include but not limited to the following: i) *Alfalfa (Medicago sativa)* dissipated TCE and TCA soil bacteria exudates; ii) *Red mulberry (Morus rubra L.)*, *crabapple (Malus fusca Schneid)*, and *orange (Maclura pomifera Schneid)* were observed to produce exudates of sufficient phenolic compounds to stimulate growth of bacteria capable of degrading PCB; iii) *Spearmint (Mentha spicata)* extracts contained a compound that induced cometabolism of a PCB iv) A *legume (Lespedeza cuneata / Dumont), Loblolly pine [Pinus taeda L.), and soybean (Glycine max L.)* were found to have mineralize TCE than non-vegetated soil; v) the use of annual *rye* and *St. Augustine grass* led to greater TPH disappearance after 21 months in a gulf field compared to the result obtained with the use of sorghum on an unvegetated plot; and vi) PAH degradation was successful through the use of mix *prairie grasses* such as big *bluestem (Andropogon gerardi)*, little *bluestem (Schizachyrium scoparius), Indiangrass (Sorghastrum nutans), switchgrass (Panicum virgatum), Canada wild rye (Elymus canadensis), western wheatgrass (Agropyron smithii), side oats grama (Bouteloua curtipendula), and blue grama (Bouteloua gracilis).*

2.6.3 Strength of Rhizodegradation

This phto-technology comes with a host of advantages which are listed by (Kafle et al., 2022) and are as follow:

- Can be implemented in-situ as all other phyto-technologies.
- Installation and maintenance cost is low compared to competing technologies.
- Translocation of contaminants to other parts of the plants or to the atmosphere is less as compared to other phyto-technologies.
- Complete mineralization of contaminants is possible.

2.6.4 Limitations of Rhizodegradation

Despite the merits listed above, rhizodegradation has its demerits as outlined by (Kafle et al., 2022) and include:

- It is a slow process and only effective in remediating contaminant in the subsurface soil (within 20 – 25 cm)
- The growth and depth of roots may be hindered by the physical structure and composition of the soil.
- Plants may need fertilizer for growth.

2.7 Phytovolatilization

Phytovolatilization occurs when plants uptake contaminants from the media, convert and release them into the atmosphere. When the contaminants are first taken up from the soil, they appear to be less volatile, therefore, the first step in phytovolatilization is to transform the less volatile contaminants into more volatile form (Limmer & Burken, 2016), this is followed by releasing the more volatile contaminants into the atmosphere. This technology is mainly suitable for organic contaminants (Limmer & Burken, 2016). Phytovolatilization can take two forms, **direct phytovolatilization** and **indirect phytovolatilization.** In direct phytovolatilization, plants uptake and translocate contaminants and ultimately volatilizes them from the stems/trunks and leaves, whereas indirect phytovolatilization refers to volatilization that occurs due to the interaction between the soil and plants in the root zone (Kafle et al., 2022). Transpiration is another process through which contaminants may be released into the atmosphere. This was reported by Li et al. (2010) when they observed trifluralin compounds to be residue bound and transpired from the leaves by ryegrass. These processes are demonstrated in Figure 2-6.

2.7.1 Mechanisms of Phytovolatilization

Phytovolatilization mechanisms include contaminants uptake, volatilization, and transpiration. During **direct phytovolatilization**, plant uptake and translocate contaminants to the shoots to diffuse across hydrophobic barriers such as cutin in the epidermis or suberin in woody dermal tissues (Choudhary et al., 2017). In the **indirect phytovolatilization** process, plants take huge amount of water from soil wherein the root activities increase the flux of volatile contaminants from the subsurface through the following processes (Choudhary et al., 2017):

- Lowering the water table.
- Water table fluctuations cause gas fluxes.
- Increased soil permeability
- Hydraulic redistribution
- Interception of rainfall that would otherwise infiltrate to dilute and advert VOCs away from the surface.

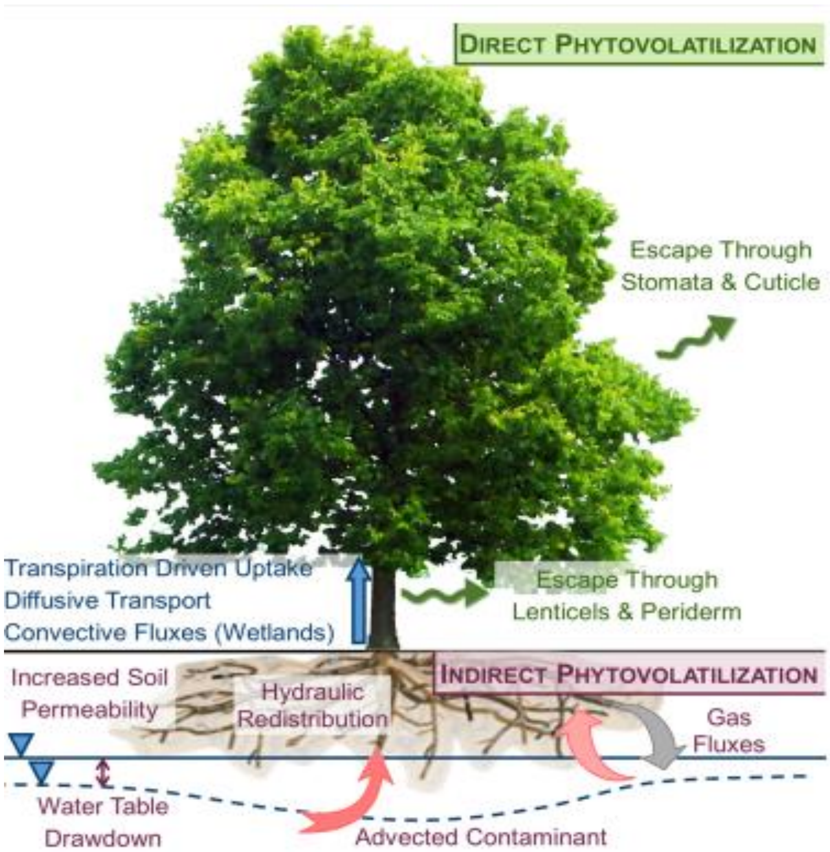


Figure 2-6: Direct and indirect phytovolatilization processes. Source:(Limmer & Burken, 2016).

2.7.2 Plants Used in Phytovolatilization

Just as in any other phytoremediation technology, selecting the right kind of plants for phytovolatilization enhances the speed and efficiency of remediation. Several plants have evolved over the years with suitable potential to manage transfer of gases such as, carbon dioxide, water vapor, oxygen, ethylene, including some molecules (Limmer & Burken, 2016). Examples of plant species that exhibited exceptional capacities of remediation through phytovolatilization include i) through a test, *Zea mays* with *Gliricidiasepium* biomass (as soil amendments) demonstrated good ability to remediate lead from a contaminated site (Muthusaravanan et al., 2018); ii) in their study of *TCE and 1,1,1-trichloroethane* (*TCA*), (Narayanan et al., 1995) reported that a notable fractions of the contaminants were volatilized by *alfalfa* (*Medicago sativa*) from soil; iii) in an outdoor experiment (mesocosm) with *baldcypress (Taxodium distichum)* planted in a gravel/sand substrate Nietch et al. (1999) observed removal of TCE, though there was fluctuations of TCE fluxes with greater fluxes during the summer than the winter; they then concluded that TCE removal was correlated to transpiration on both seasonal and daily scales, suggesting that TCE advected with the transpiration stream; and iv) also investigating plants ability to volatilize methyl tert-butyl ether (MTBE), Hong et al. (2001) dosed hydroponic *hybrid poplars with 14C-MTBE* for 10 days and results showed a 17% direct volatilization of total MTBE, representing 96% of the total MTBE translocated by the trees.

2.7.3 Strength of Phytovolatilization

Phytovolatilization is noted for the following advantages (Limmer & Burken, 2016):

- Transformation of contaminants into less-toxic forms; for example, elemental mercury and dimethyl selenite gas
- The release of contaminants into the atmosphere provides opportunity for contaminants to be more degraded by natural degradation processes.

2.7.4 Limitations of Phytovolatilization

However, there are some disadvantages connected to the application of phytovolatilization as outlined below (Limmer & Burken, 2016):

- Phytovolatilization may promote the accumulation of contaminants in the vegetation and later be passed on to receptors through fruits, for example.
- Metabolite, such as vinyl chloride formed from TCE, may be released into the atmosphere, thus creating more environmental problem.

2.8 Hydraulic Control

In hydraulic control, plants are used to control the movement / flow of groundwater thus controlling the transport of contaminants from contaminated site. Hydraulic control is also referred to as phytohydraulics or hydraulic plume control and it is defined as the use of plants to remove groundwater through uptake and consumption to contain or control the migration of contaminants (Sharma & Pathak, 2014). It is also defined as the control of the water table and the soil field capacity by plant canopies (Etim & Etim, 2012).

2.8.1 Mechanisms of Hydraulic Control

During hydraulic control, the increased transpiration by plants reduces the infiltration of precipitation thus reducing leaching of contaminants from the vadose or unsaturated zone (Sharma & Pathak, 2014). Hydraulic control also happens with increased transpiration of groundwater, thus reducing contaminant migration from the site in groundwater plumes (Etim & Etim, 2012). Figure 2-7 describes the process of hydraulic control.

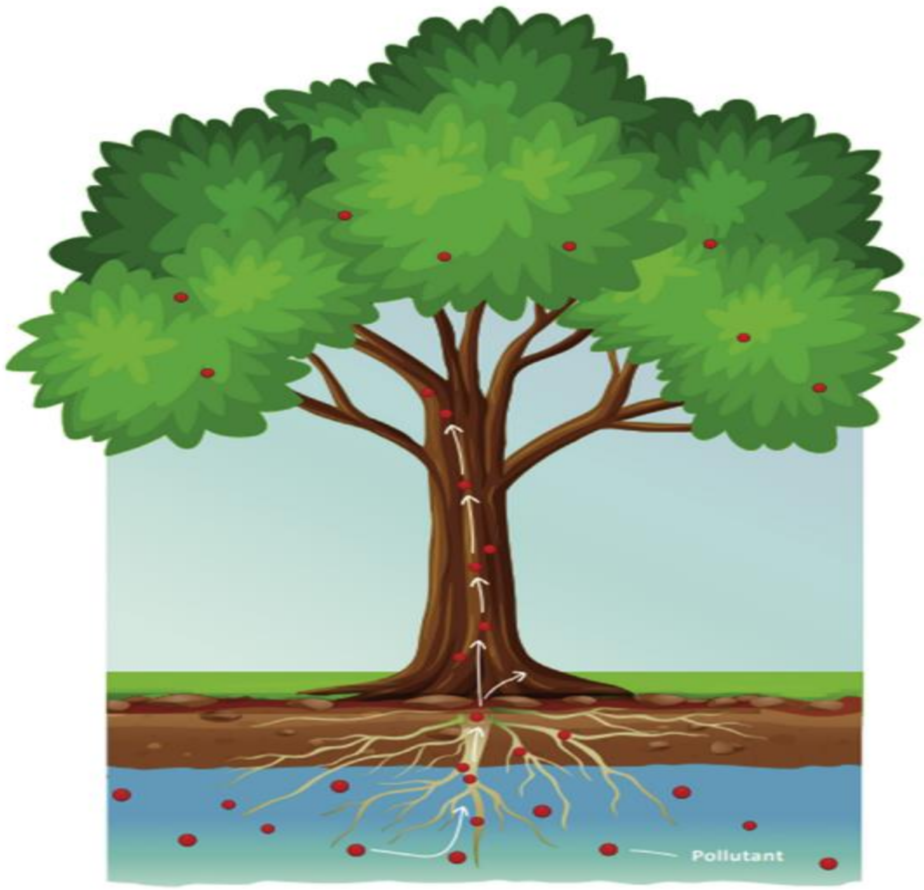


Figure 2-7: Phytoremediation through hydraulic control. Source: (Tonelli et al., 2022).

2.8.2 Plants Used in Hydraulic Control

The goal of hydraulic control is to affect the existing water balance to prevent contaminated groundwater from reaching the receptor (i.e., well, lake or stream), therefore when selecting plants to be used in hydraulic control, one needs to consider phreatophytic trees and plants with the ability to transpire large volumes of water (Etim & Etim, 2012) to have noticeable effect on the water table. Examples of plants that have demonstrated good abilities for hydraulic control include i) containment and remediation of shallow groundwater contaminated with heavy metal, nutrients and pesticides using *cottonwood* and *hybrid poplar* trees in the East and Midwest; and ii) gasoline and diesel contaminated groundwater was remediated using *poplars* in Utah, USA (Sharma & Pathak, 2014).

2.8.3 Strength of Hydraulic Control

Hydraulic control advantages include the following (Sharma & Pathak, 2014):

- Hydraulic control is better than a pumping well since plant roots will penetrate and stay in contact with groundwater at a deeper depth.
- Cost-effective
- No need to install a pump-and-treat system.

2.8.4 Limitations of Hydraulic Control

The following are the disadvantages of hydraulic control (Sharma & Pathak, 2014):

- The efficiency of hydraulic control is climate dependent.
- The uptake of groundwater is limited by depth of roots.

2.9 Phytoremediation Projects

2.9.1 Planning and Design

Like any other project, a proper planning of phytoremediation project sets the basis for its efficiency. It is difficult or impractical to specify a particular set of steps or plans that fit all sites because every phytoremediation project is designed depending on the prevailing site conditions. However, the general layout of planning and designing any phytoremediation project includes assessment, site characterization and investigation and analysis of data obtained, deciding treatment methods, site preparation and planting (Boros et al., 2016).The practical way to enhance phytoremediation is to prepare a detailed program about the contaminated site which should contain a complete list of all data to be collected and all analytical tests, methods and research techniques that should be followed (Boros et al., 2016). It is also important to involve all parties from the initial stage of the planning. In their study about contaminated sites, Drenning et al. (2022), proposed a GRO risk management framework that can be used to support stakeholders such as decision makers, regulatory bodies, and contractors. According to the study, the framework can be used as a tool to facilitate remediation of contaminated sites by communicating risk mitigation mechanisms and timeframes and to classify the prospects for the application of GRO after a complete site investigation (Drenning et al., 2022). In Figure 2-8 steps followed in planning and implementing a phytoremediation project for phytoextraction is demonstrated.

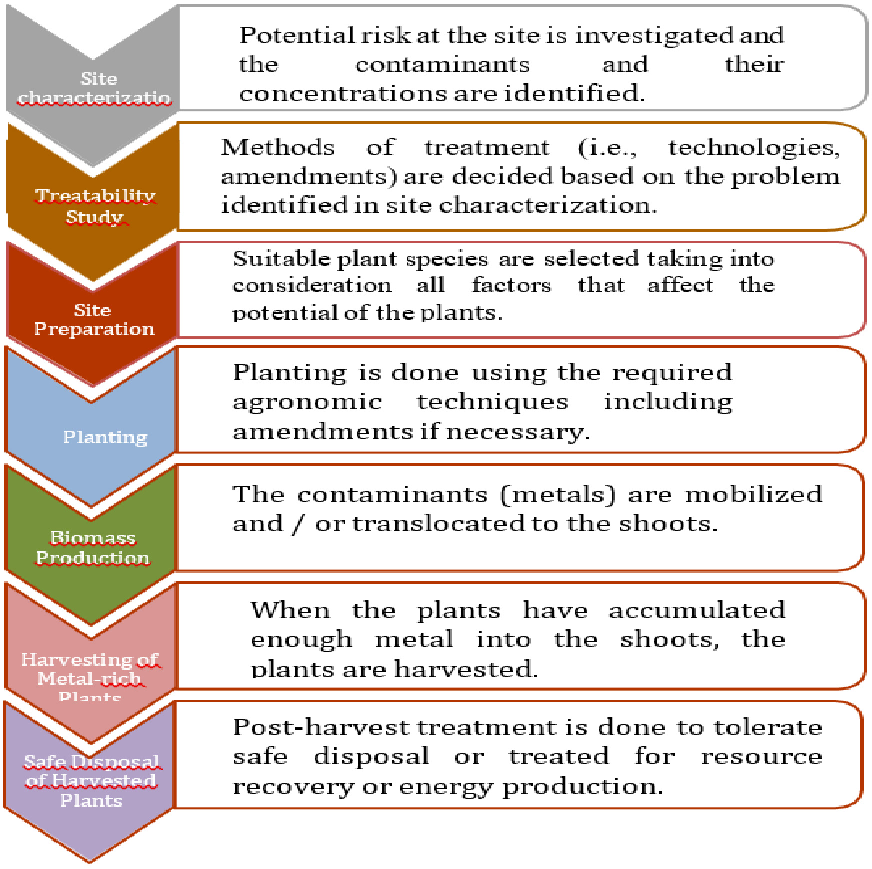


Figure 2-8: Scheme of the phytoremediation programme plan.Source:(Boros et al., 2016)

2.9.2 Operation and Maintenance

Phytoremediation mechanisms and processes involve plants interaction with microorganisms. To ensure the optimal operation of these interactions and the processes involve, proper maintenance and management is crucial. The phytoremediation technology is subject to interruptions from factors such as climate action, invasive insects, and animals (Green & Hoffnagle, 2004). The system must be monitored at a regular interval to arrest and remedy any actions that may undermine its efficiency. During an experiment at Linnaeus University in Sweden, the process was destroyed by fungus invasion which spread from the polluted greenhouse and the invasion from a huge number of insect larva which ate all ripe plants within two days (Green & Hoffnagle, 2004) (Chang & Hogland, 2022). Typical maintenance in a phytoremediation project involves visual inspections, the use of fertilization, irrigation, weed control, pest Control, and replanting (Green & Hoffnagle, 2004).

The use of aids in phytoremediation is another important factor for improving the efficiency of remediation. The aids can be natural or chemical amendments, microbial enhancement, or genetic engineering (Sharma & Pathak, 2014). The benefits of aids in phytoremediation include i) improve the formation of metals - chelators complexes; ii) increase plant resistance and tolerance level to metals; and iii) enhance translocation and accumulation of metals within the plants (Sharma & Pathak, 2014). In Table 2-1, typical amendments / enhancements used in phytoremediation are listed with their associated effects.

Table 2-1: Phytoremediation aids, mechanisms involved and their effect in phytoremediation (SBR = Sugar beet residue, EDTA = Ethylenediaminetetraacetic acid, EGTA = Ethylene glycol tetra acetic acid, SDS = sodium dodecyl sulfate, PGPR = Plant growth promoting rhizobacteria, PGPE = Plant growth promoting endophytic bacteria, AMF = Arbuscular mycorrhizal fungi) Source: (Sharma & Pathak, 2014).

Type of Amendment	Classification	Effects
SBR	Natural Amendment	Increases microbial biomass and activity; increases metal bioavailability and phytoextraction
Composted sewage sludge	Natural Amendment	Increase metal bioavailability and phytoextraction
Paper waste	Natural Amendment	Improves plant growth and soil physical properties
Biochar	Natural Amendment	Improves nutrients cycling, water and nutrients retention, increase plant biomass and reduces metal solubility
EDTA	Chemical Amendment	Metal – chemical complexation, enhance metal uptake
EGTA	Chemical Amendment	
SDA	Chemical Amendment	
PGPR	Microbial Enhancement	Increase production of organic acids and enzymes; increase metal bioavailability and uptake; lower ethylene production; increase bacteria auxin production; improve plant growth, root hair development and resistance to metal.
PGPE	Microbial Enhancement	
AMF	Microbial Enhancement	Facilitates oxidative enzymes in the rhizosphere and initial ring cleavage aromatic hydrocarbons; increase absorptive surface area in root and improves nutrients, water, and metal uptake
Gene transfer, manipulation, and cloning	Genetic Engineering	Overexpresses gene involve in metal transport and uptake; increases plant biomass and tolerance to metals, oxidative stress mechanisms

2.9.3 Cost Analysis

The cost of phytoremediation varies, as it depends on several factors. Phytoremediation promises to be cost-effective when compared to other conventional methods due to its low start-up cost and a very low or negligible operational and maintenance costs (Zodrow, 1999). Though phytoremediation is not the best alternative for every site, especially when contaminants concentrations are above low or moderate levels, but it has shown great potentials, in several studies, at remediating lead, cadmium, zinc, radionuclides and other organic contaminants (Compernolle et al., 2012; Gatliff, 1994; Nyer & Gatliff, 1996; Zodrow, 1999). Therefore, when comparing the cost of phytoremediation to the cost of other methods, it is appropriate to consider the site conditions such as contamination level, depth of soil or groundwater, time require for the project etc. because there is a strong correlation between the cost of phytoremediation and the type and level of contamination, the media characteristics, and the land use (Farraji et al., 2016).

Studies to substantiate the cost-effectiveness of phytoremediation are advancing. In a case study, Nyer & Gatliff (1996) compared the cost of phytoremediation and conventional pump-and-treat method in remediating a 1-acre size and 20-ft deep aquifer contaminated with heavy metal. In the cost comparison, cost common to both approaches was not considered (i.e., meeting with stakeholders, permitting and laboratory analysis). The results established US$250,000 and US$660,000 for phytoremediation and pump-and-treat respectively, indicating that phytoremediation was cost-effective compared to pump-and-treat. Table 2-2 presents the items included in the comparison.

Table 2-2: Estimated Costs of remediating 1-Acre Site with 20-Foot-Deep Aquifer. Source: (Gatliff, 1994)

Pump-and-Treat[a]	
Equipment	$100,00
Consulting	25,000
Installation/construction	100,000
5-year costs	
Maintenance	105,000
Operation	50,000
Waste disposal	180,000
Waste disposal liability	100,000
Total	**$660,000**

[a] Assuming off-the-shelf equipment, three pumping wells, and a reverse osmosis treatment system.

TreeMediation	
TreeMediation program design and implementation	$50,000
Monitoring equipment	
Hardware	10,000
Installation	10,000
Replacement	5,000
5-year monitoring	
Travel and meetings	50,000
Data collection	50,000
Annual reports	25,000
Effectiveness assessment—sample collection and analysis	50,000
Total	**$250,000**

In a 16-scenario study, (Chen & Li, 2018) conducted a cost-effectiveness analysis for excavation and disposal, soil washing and phytoextraction in treating heavy metal contaminated sites. In the study, literature review was used to gather different soil texture, site scale, soil metal, and the level of contamination. Table 2-2 gives the concentration ranges for heavy metal considered in the study. From the simulated results, it was established that phytoextraction was more cost effective when dealing with slightly contaminated sites while soil washing emerged as cost effective in severely contaminated scenarios. The results are displayed in Figure 2-9

In his investigation of the cost-effectiveness of phytoremediation, Zodrow (1999) compared the cost of using excavation and disposal and phytoremediation to remove Pb from a contaminated site of 10-acre to a depth of 1ft at a concentration level of 500 ppm. The study reported the total volume of excavated soil to be about 30,000 tons at a cost ranging from $350,000 to $450,000 compared to the cost of phytoremediation (involving purchase of plants, fertilizers, labor, and equipment for cultivation) between \$100,000 and \$120,000.

Table 2-3: Heavy metal concentration ranges in soils worldwide reported in literatures. Source: (Chen & Li, 2018).

Metals	Min concentration (mg kg^{-1})	Max concentration (mg kg^{-1})
As	0.1	252.5
Cd	0	1458
Cr	0.05	10,000
Cu	0.1	1790
Hg	0	1800
Ni	0	5000
Pb	0.1	69,000
Zn	0.3	57,012
Mn	3.0	42,600

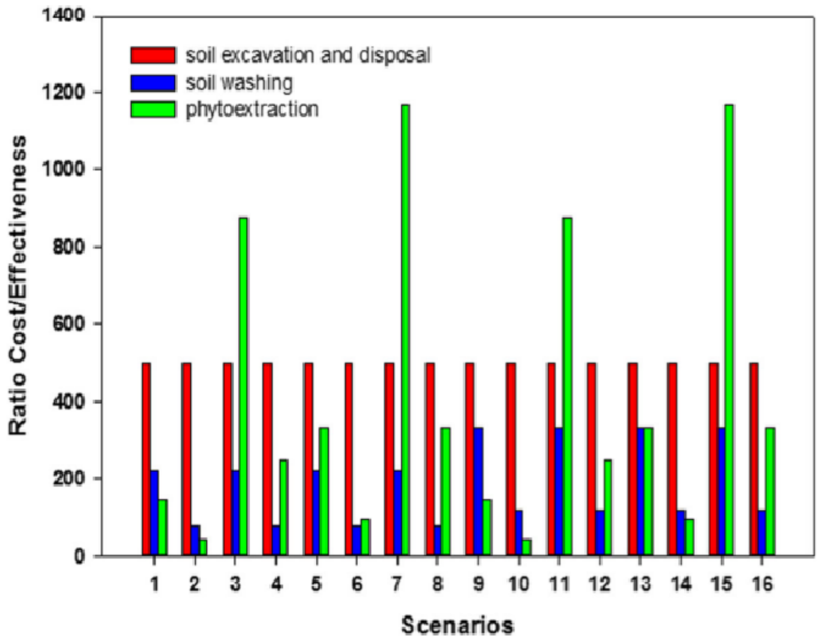


Figure 2-9: Comparison of cost-effectiveness ratios of soil excavation and disposal, soil washing, and phytoextraction (5 years). Source: (Chen & Li, 2018).

2.10 Databases

A database is one of the major tools for researchers, it can be described as an inventory of data stored and then retrieved when needed. A database is a useful way of managing and sharing data. Scientific databases are different from business-oriented databases ('Jones et al., 1990). Every time research is conducted, thousands of data are gathered. These data are then used to analysed and answer research questions and the results are published where the data that contributed to the results are filed and rarely accessible (Porter, 2018).This traditional model of data treatment is unnecessary and waste of effort and time because subsequent researchers within the same field cannot utilize the previously collected data. According to 'Porter (2018), when the kind of research needed to address some demanding questions (i.e., environmental problems) are not localized in space or time, then traditional model is a failure. Research cannot flourish without data that can be preserved and made accessible and this is true especially in scientific research where scientific data collection requires data resources as compared to just the need of logistics to collect data (Porter, 2018). Engineers and researchers should integrate efforts and support one another in their research by sharing data to synthesize and enhance data analysis. This collaborative effort can only be made possible with a well-developed databased. In scientific research, such as environmental research, complex processes are studied, for example, changes in ecosystem, transport of contaminants and remediation processes (Porter, 2018). The analysis and understanding of these processes require collaborative efforts of researchers rather than discretely collected data. The data involved in the scientific studies must be analysed over decades to draw conclusions. This is why 'Porter (2018) stated that the requirement of long-term curation of data and the need for data exchange between scientists to support integrative and synthetic analyses are facilitated by the development of databases at several different levels, from the investigator to the institution and even to the discipline.

Types of Databases

A database may be considered as "deep" or "wide" depending on the type of data and the way the data are stored (Porter, 2018). A "**deep**" database uses single or few datasets to carry on sophisticated search and have great analytical potentials (Porter, 2018). Example of this type of database include i) UniProt Knowledgebase which contains over 80 million sequences(Bateman et al., 2015); ii) the Research Collaboratory for Structural Bioinformatics Protein Data Bank (Berman et al., 2000).

The "**wide**" type of database is, on the other hand, is a data reservoir which seeks to capture all datasets associated with a specific field of science such as environmental research (Porter, 2018). Examples of a "wide" type of database include i) the National Centers for Environmental Information (NCEI) which contains over 20 petabytes of oceanic, atmospheric and geophysical data and operated by the National Oceanic and Atmospheric Administration (NOAA) (Porter, 2018); and ii) the Distributed Active Archive Centers (DAACs) operated by the National Aeronautics and Space Administration (NASA); each of these centers have different number of various types of datasets in the area of earth or space science (Porter, 2018). The differences between the two types of databases are summarized in Table 2-4.

Under the "wide" database is another type of database which captures a wide array of data focusing on a particular site or research question. These are called project-based database and support a particular multidisciplinary research project (Porter, 2018). Some examples of project-based databased are listed in ’Porter (2018) and include Long-Term Ecological Research (LTER) which deals with data relating to a wide range of scientific topics (i.e., weather and climate, primary productivity, nutrient movements, organic matter, trophic structure, biodiversity, and disturbance). For the purpose and scope of this study, the project-based database is of essence since a wide range of data about plant selection are collected and stored in a software.

Table 2-4: Difference between Deep Database and Wide Database. Source:(Porter, 2018)

DEEP DATABASE	WIDE DATABASE
• Specialize on one or a few types of data • Large numbers of observations of one (or few) type(s) of data • Provide sophisticated data query and analysis tools • Tools operate primarily on data content	• Contain many different kinds of data • Many different kinds of observations, but relatively few of each type • May provide tools for locating data, but typically do not have tools for analysis • Tools operate primarily on metadata content

2.10.1 Advantages of Databases

There are several advantages associated with the development and use of databases in research. Some of these are taken from (Porter, 2018), presented, and discussed below:

- **Improvement of the overall quality of data:** with database, the detection and correction of discrepancies in the data is possible because of multiple users.
- **Cost:** researchers working on the same objectives will save data collection cost and make use of previously collected and stored data. Environmental data collection is influenced by some uncontrolled factors such as weather, but with a database this problem can be avoided.
- **Encourage data sharing:** long-term studies use database to retain project history, for example. Also, databases make it possible to integrate diverse data resources in ways that support decision-making processes.
- **Data synthesis:** data from a database can be used in other studies other than for which the data was originally collected.

Despite all the merits listed above, databases have some drawbacks which are listed and discussed below (Porter, 2018):

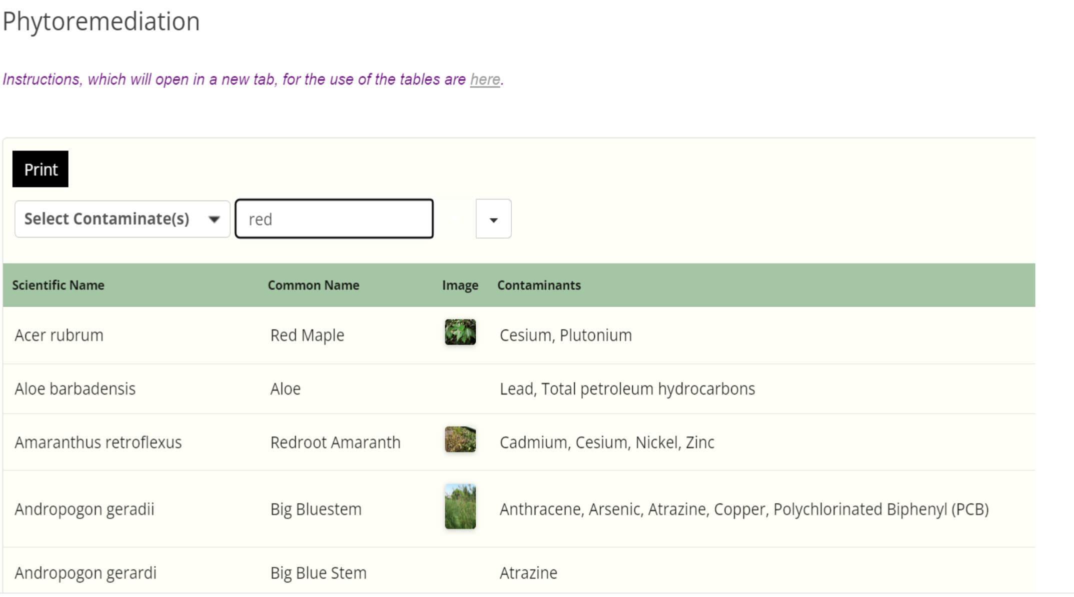
- ***Dealing with diversity in data:*** scientific database needs to be adaptable so that they can support new kinds of queries.
- **Unlike commercial database**, scientific database may contain data of different observation of similar phenomenon due to methodology, model and precision used in collecting and compiling such data. To overcome these limitations, Costello (2009); Meeson & Strebel (1998) proposed the publication model of database rather than the traditional model where data are rarely altered once stored in the database.
- **Long-term data storage:** in a business-oriented database, maintaining data for a long period of time is not necessary (i.e., inventory, payroll, etc), on the contrast, scientific database requires data to be stored and accessed on a long-term basis to allow researchers access changes that would otherwise be invisible.

2.11 Existing Databases for Phytoremediation and their Functionality

There are several other databases that are being developed to increase the accessibility of research results about plants potential in phytoremediation. This section provides examples of databases that have been developed to increase access to the phytoremediation studies.

2.11.1 A User-Friendly Phytoremediation Database

The "user-friendly phytoremediation database" is a collection of research results of plants species developed by an Environmental Artist & Professor of Landscape Architecture, Stevie Famulari, assisted by a landscape architecture student, Kyla Witz (Famulari & Witz, 2015). The database highlights the broader implication associated with databases in phytoremediation and includes data on plant species potential, and aids used to enhance phytoremediation. The database allows users to search for plants by scientific and common names, contaminants name and types and full citations to the original studies. It also includes the photograph and specific qualities of the plants. It is built on a website and contains two sections: the data search section and the terminology section. The former is used to search data of interest while the latter assists the users with explanations of terminologies and acronyms used in the database. The data search section is divided into two search tables. The first table (shown in Figure 2-10) allows users to search for plants (by scientific and common names), contaminants, and technologies while the second table (shown in Figure 2-11) allows users to search contaminants by type. According to the developer of the database, she saw the need to develop such a database after practising environmental art and landscape design for many years and saw the gap in public accessibility of phytoremediation research results (Famulari & Witz, 2015). The developer described the users as scientific and non-scientific, meaning experts and non-experts.


Phytoremediation

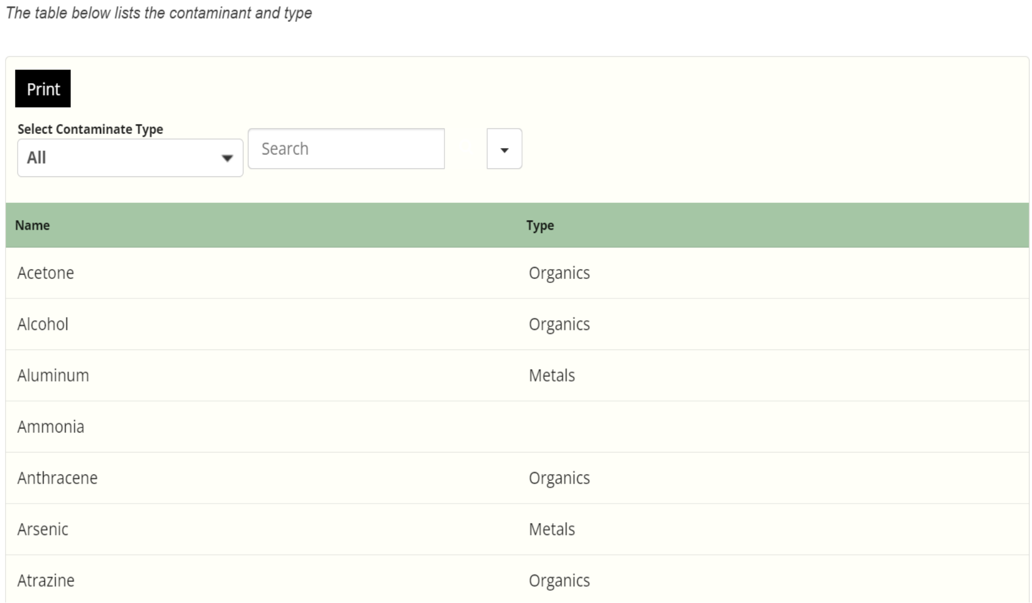
Instructions, which will open in a new tab, for the use of the tables are here.

Print

Select Contaminate(s) | red

Scientific Name	Common Name	Image	Contaminants
Acer rubrum	Red Maple		Cesium, Plutonium
Aloe barbadensis	Aloe		Lead, Total petroleum hydrocarbons
Amaranthus retroflexus	Redroot Amaranth		Cadmium, Cesium, Nickel, Zinc
Andropogon geradii	Big Bluestem		Anthracene, Arsenic, Atrazine, Copper, Polychlorinated Biphenyl (PCB)
Andropogon gerardi	Big Blue Stem		Atrazine

Figure 2-10: Search table 1 for user-friendly phytoremediation Database. Source: (Famulari & Witz, 2015).



The table below lists the contaminant and type

Print

Select Contaminate Type: All | Search

Name	Type
Acetone	Organics
Alcohol	Organics
Aluminum	Metals
Ammonia	
Anthracene	Organics
Arsenic	Metals
Atrazine	Organics

Figure 2-11: Search table 2 for user-friendly phytoremediation Database. Source: (Famulari & Witz, 2015).

2.11.2 Global Hyperaccumulators Database

In an effort to find solution to the problem encountered in structuring all the metal-tolerant species into a user-friendly database, the **Global Hyperaccumulators database** was developed and is being managed by the center for Mined Land Rehabilitation of the University of Queensland in Brisbane, Australia (Reeves et al., 2018). Information reported into this database includes the *taxonomy, distribution, ecology, collection records, analytical data, and references*. The developer of the database attached certain criteria that the plant species must meet before being reported into the database. These criteria include i) species must contain in their dry weight foliar tissue > 100 µg g^{-1} cadmium, thallium or selenium, > 300 µg g^{-1} of cobalt, copper or chromium, > 1000 µg g^{-1} of nickel, arsenic, lead, or rare earth elements (REEs), > 3000 µg g^{-1} of zinc, or > 10 000 µg g^{-1} of manganese, when growing in their natural habitat (Reeves et al., 2018). In addition to these criteria, the developer of the database does not accept species that obtained the set threshold criteria mentioned above by growing them under condition such as hydroponic or growth in spike soil or by using chelators to achieve abnormal foliar accumulation. Among other things, the Global Hyperaccumulators Database serves the following purposes: i) provide access to data from sources that are difficult to locate; ii) give details that may not have been published in the open literature; iii) monitor and update nomenclatural changes; and iv) raise awareness of the plight of many hyperaccumulator species that are under threat of extinction (Reeves et al., 2018).

2.11.3 PhytoPet Database

The PhytoPet is a Canadian database containing plant species with the potential to phytoremediate and/or tolerate petroleum hydrocarbons. The idea to develop this database was derived as a result of the lack of knowledge of the availability and selection of suitable plants for the phytoremediation of petroleum hydrocarbons under Canadian climatic and ecological conditions (Farrell et al., 2000). The database was designed using the Microsoft Access 97. This software is compatible with other databases developed in spreadsheets formats (Farrell et al., 2000). The purpose of the PhytoPet database is to serve as an inventory of plant species with the potential to phytoremediate or tolerate petroleum hydrocarbons in terrestrial and wetland environments (Farrell et al., 2000). Data in the database are structured under three main categories which include *summary information, experimental data, and plant specific data.* The summary information category provides a brief description of the plant and associated mechanism of phytoremediation, the experimental data category, with two section, provides a detailed summary of the experimental conditions in each study included in the database while the plant specific data category includes information on the taxonomy, habitat, biology, and distribution of each plant in the database. When a user login to the database, a dialog box with four buttons, as shown in Figure 2-12, appears and guides the user in their data search while Figure 2-13 shows the multiple queries platform of the database.

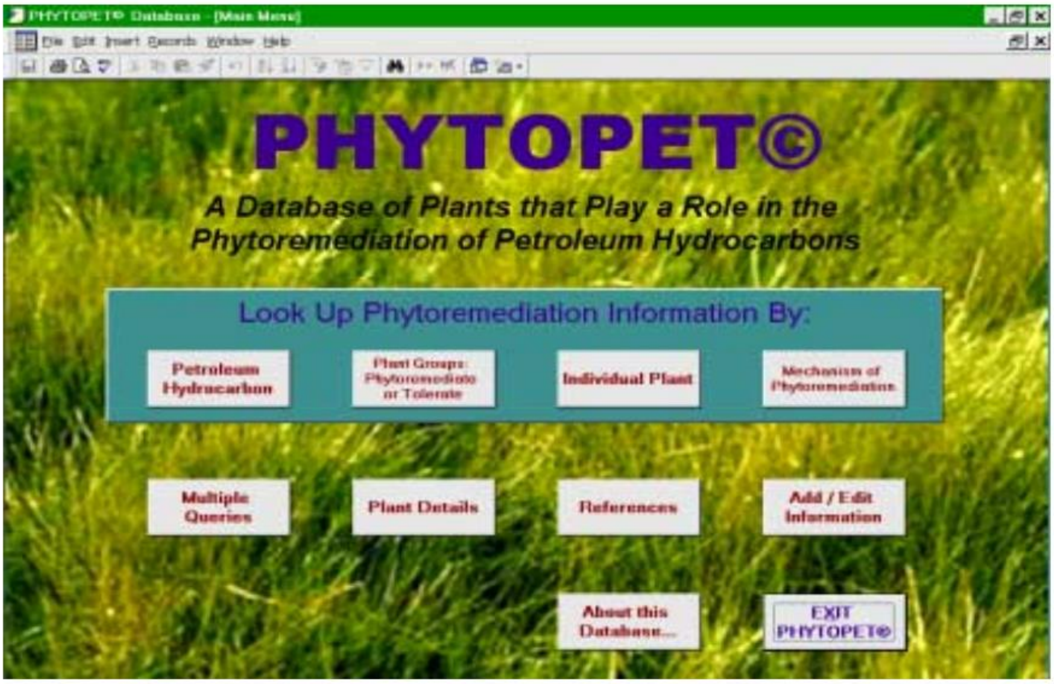


Figure 2-12: Structure of the PhtoPet Database. Source:(Farrell et al., 2000).

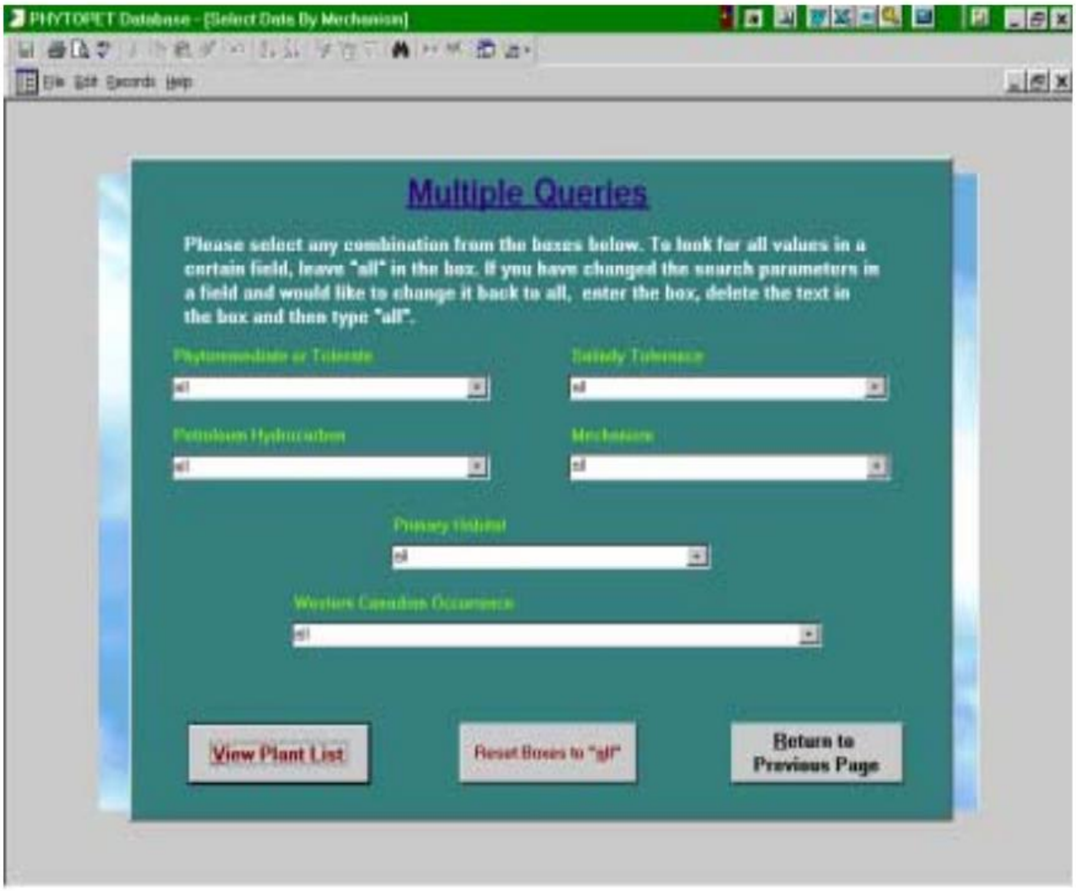


Figure 2-13: Multiple Quiries platform for the PhytoPet Database. Source: (Farrell et al., 2000).

3 Method

This section describes the steps that were followed to complete this project. As presented in Figure 3-1, the steps include data collection, literature search, mini survey, workshop, climatic zones classification, exploration of existing databases and suitable freeware selection.

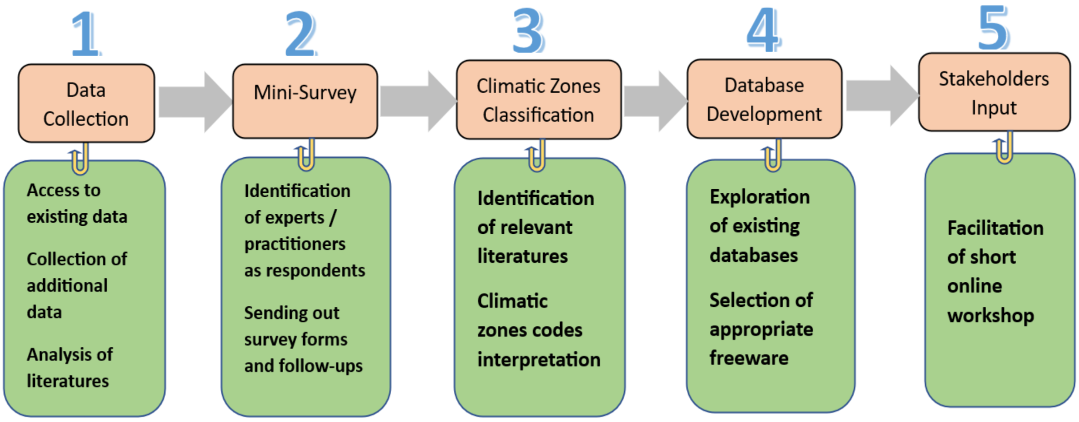


Figure 3-1: Schematic of processes / steps followed in the master thesis project.

3.1 Data Collection

3.1.1 Existing Data

The first set of data use in this master thesis was compiled by Paul Drenning (Drenning, 2021). In a literature review, Paul gathered data from different pilot and field studies conducted in Europe, North America, and Asia. The studies included 69 different pot and field studies about plant species potential in phytoremediation. 7.2% of the studies are pot studies while 92.8% are field studies. The data collected by Drenning (2021) include location of the studies, the contaminants, plant species, GRO technology used, enhancements, duration of the studies, brief description of the results and references to the original studies. The compilation also includes comments about the studies, which describe the challenges and recommendations by the authors.

3.1.2 Additional Data

As an addition to the existing dataset, a strategic literature search was done to identify more pilot and field studies. Since the initial dataset focused on Europe, North America, and Asia, it was deemed appropriate to include studies from other continents to have a fair representation of climatic zones. The strategic literature search was also done to gather relevant literatures to support the background and theory chapters of this report.

Strategic literature search is a method which uses the concept of key terms from research question to retrieve relevant literatures for use in research works. This methodology follows a set of systematic steps which include identification of key terms and their synonyms, construction of search blocks and development of search strings (Kable et al., 2012). There are several literature databases which use different search operators to carry out systematic literature search. In this thesis, the Scopus database and Google Scholar, and the Boolean Operators ("AND" and "OR") were used (Gillespie & Gillespie, 2003). To obtain relevant literatures about the topic, Key terms were identified and based on the key terms, search strings were formulated. After performing the initial search, the results were browsed through to check whether the results contain relevant literatures. Whenever it was established that results contain unrelated literatures, the search strings were modified by either using synonyms of key terms or by replacing or interchanging the Boolean Operator (OR / AND). Table 3-1 summarizes the results obtained from the strategic literature search.

Table 3-1: Summary of Strategic Literature Search Results.

Key Terms	Operator	Search String	Search Engine	Results
Plant Species Phytoremediation Pot Studies Field Studies Climatic Zones	"AND" "OR"	((Phytoremediation AND Plant AND Selection) AND (Pot Studies OR Field Studies))	Scopus	30
		((Phytoremediation AND Plant Selection) AND (Climatic Conditions))	Scopus	7
Phytoremediation	"AND"	(Phytoremediation AND Searchable AND Scientific Databases)	Google Scholar	*17k +
Database Scientific Searchable		(Searchable AND Database AND Software)	Scopus	23
Phytoremediation Mechanisms Technologies	"AND"	(Phytoremediation AND Mechanisms AND Technologies)	Scopus	641

* *Only the first ten pages of results were browsed and only checking for journal articles*

3.1.3 Analysis of Search Results (Data Quality Check)

One of the important factors to consider when searching literature is to analyze the results. This is done to ensure that relevant and applicable literatures are identified for the research work and that all sources are credible enough for the robustness of the research. There are several methods / techniques used to analyze search results including conducting quality inspection of the searched literatures by considering a set of inclusion and exclusion criteria (Gillespie & Gillespie, 2003; Kable et al., 2012). In this master thesis, the following criteria, as recommended by Kable et al. (2012b), were used to analyze the results and to select relevant literatures used throughout this report:

1. Literature contains relevant information about the topic.
2. Number of times the paper has been cited.
3. Year of publication
4. Number of readers and
5. Whether the literature is a journal article (only for Google Scholar database)

These criteria were evaluated by looking up the statistics that accompanied each source in the Scopus and Google Scholar (only first ten pages were browsed) databases except for criteria 1 which was assessed by reading the abstracts, introductions, and conclusions of the literatures. For results that stretched over two pages, only the results of the first two pages were considered in the quality check. After the results analysis, 98 literatures were found to meet all criteria and thus used in this master thesis report.

3.2 Inputs from Stakeholders and Experts

The stakeholders who contributed to this master thesis include engineers and researchers working with contaminated sites in Sweden. Some of them are employees of various companies and universities in Sweden while others work for government agencies such as Swedish Geotechnical Institute (SGI), Swedish Geological Survey (SGU). Yet, others are individual researchers and owners of phytoremediation companies. It is believed that their input to this project is a great contribution to the quality of data contained in the database.

3.2.1 Stakeholders / Experts Needs – A Mini Survey

To complement the data gathered from literature review, a survey was conducted among practitioners and researchers. The respondents in the survey were selected from across various companies in Sweden who are working with contaminated sites. The decision to run a survey was based on the assumption that respondents will provide more practical input for the development of the database since they have been working with contaminated sites and have some experience. Also, it was deemed reasonable to gather some data from practitioners and researchers locally since it is expected that most of them will work with the database in their henceforth.

3.2.2 Database Evaluation by Stakeholders / Experts

A short online workshop was organized for stakeholders. Prior to the workshop, a copy of the database was sent out to participants for review / or trial. During the workshop, the scope and limitations of the database was explained. A demonstration of how the database can be used and what data can be searched was done. The purpose of the workshop was to get stakeholders / experts feedback about the functionality of the database, the overall structure and whether the data contain in the database are relevant.

3.3 Climatic Zones Classification

The Koppen-Geiger climate map was used to estimate the climatic zones of each study area. Koppen-Geiger climate map is complemented by a legend which explains the climatic zones of each country. By carefully studying the map of the country in which the study was performed, it was possible to estimate the climatic zone using the color coding. To reduce the uncertainty in the estimation of the climatic zones, literatures about the climate of each study site were reviewed. For example, there are four main climate types in Europe which include **D, B, C and E** covering 44.4%, 36.3%, 17.0% and 2.3% of land respectively (Kottek et al., 2006). With this information, it was easy to avoid erroneous estimation of the climatic zones (i.e., it is not reasonable to estimate a climatic zone of a study site in Europe as climate type **A** since Europe has no such climate type). The climatic zone of each study area is further sub-categorized to describe the specific variables that define the climate condition. For instance, England and Poland are found under the same type **C** climatic zone but have different sub-climatic zones of **Cfb** and **Cfc** respectively, meaning England has warm summer while Poland has cold summer, but both countries have warm temperate climate. The climatic zones classification (presented in Table 3-2), are defined by certain criteria such as temperature ranges, and annual precipitation (Kottek et al., 2006; The GLOBE Program, 2000).

Table 3-2: Definitions of climatic zones codes. Source: (Beck et al., 2018; Kottek et al., 2006).

Color	Code	Main Climate	Precipitation	Temperature
	Af	Equatorial	Fully humid	
	Am	Equatorial	Monsoonal	
	As	Equatorial	Summer dry	
	Aw	Equatorial	Winter dry	
	BWk	Arid	Desert	Cold arid
	BWh	Arid	Desert	Hot arid
	BSk	Arid	Steppe	Cold arid
	BSh	Arid	Steppe	Hot arid
	Cfa	Warm Temperate	Fully humid	Hot summer
	Cfb	Warm Temperate	Fully humid	Warm summer
	Cfc	Warm Temperate	Fully humid	Cold summer
	Csa	Warm Temperate	Summer dry	Hot summer
	Csb	Warm Temperate	Summer dry	Warm summer
	Csc	Warm Temperate	Summer dry	Cold summer
	Cwa	Warm Temperate	Winter dry	Hot summer
	Cwb	Warm Temperate	Winter dry	Warm summer
	Cwc	Warm Temperate	Winter dry	Cold summer
	Dfa	Snow	Fully humid	Hot summer
	Dfb	Snow	Fully humid	Warm summer
	Dfc	Snow	Fully humid	Cold summer
	Dfd	Snow	Fully humid	Extremely continental
	Dsa	Snow	Summer dry	Hot summer
	Dsb	Snow	Summer dry	Warm summer
	Dsc	Snow	Summer dry	Cold summer
	Dsd	Snow	Summer dry	Extremely continental
	Dwa	Snow	Winter dry	Hot summer
	Dwb	Snow	Winter dry	Warm summer
	Dwc	Snow	Winter dry	Cold summer
	Dwd	Snow	Winter dry	Extremely continental
	EF	Polar frost		
	ET	Polar tundra		

3.4 Database Development

The development of a database is an evolving process which means it should be built in a way that allows changes to meet current realities and accommodate feature development.
To ensure that the database serves the purpose and aims of this master thesis, the following three questions were answered as recommended by (Porter, 2018).

- **Why is the database being developed?** Some databases are needed to address some immediate research questions for a short period of time while others will preserve data over a long period of time to solve some scientific problems. Therefore, knowing the purpose of the database is a major factor in developing a database that will be appropriate for the research. For this master thesis, the database is developed to serve as repository of research data that will be accessed by practitioners from time to time.
- **Who will use the database?** This is a very important question to answer before going on to deciding the structure of the database and the selection of suitable software. If

database users are defined, it will inform the developer as to what sophistication the database should have. For example, database meant for experts will not be useful for non-experts and the technology / software used must be available to user, otherwise the database will not be utilized. For this database, the users are experts and non-experts who are interested in the application of phytoremediation.

- **What questions does the database seek to answer?** Knowledge of questions that the database should answer helps the developer in organizing the data, what criteria should be searchable and what results should be returned. For this database, answers to scientific questions regarding the potential of plant species in remediating contaminated sites are expected to be obtained.

3.4.1 Exploration of Existing Databases

Existing databases were explored to learn about other efforts that are being undertaken to increase access to information about plants performance in phytoremediation. Exploration of databases was necessary as it provided the opportunity to study the type of data included in similar databases, their structure and functionality. With this, it was easy to decide an appropriate structure and functionality of the database and to ensure that relevant data are included into the database. There are challenges in developing scientific databases, looking up other databases and how they were developed, assisted with overcoming those challenges and to develop a database that aligns with typical databases in similar research.

3.4.2 Selection of Suitable Software for the Database

The developer of a database should consider the following factors: i) is the software free or commercial? and ii) can the software be easily installed? A free software will attract multiple users, and this provides opportunities for testing the performance of the database (Porter, 2018):

It was deemed appropriate to use a free software (i.e., does not require fees other than subscription to Microsoft package) for the development of the database since the database is intended for a wide range of users. To facilitate the software selection, a number of free software was explored to compare their capacity in storing and handling data. The software selection also considered the fact that the database performs tasks such as queries, sorting, and data input. The following criteria were used to select the software for the development the database:

1. **User-friendly:** the purpose of this criterion is to allow both practitioners and non-practitioners to use the database. For example, homeowners, farmers, gardeners etc. can easily use the database to carry out small remediation projects.
2. **Data Sorting Feature:** the database should be able to sort both numerical and texts data so that user can easily locate their desire data.
3. **Freeware:** since the database is meant to be available to everyone, it was deemed necessary to develop it using a software that does require fees, other than subscription to Microsoft suit. This way, anyone can download the database and store it in their system.

4 Results

4.1 Additional Data Collected from Literature Review

To increase the robustness of the database, additional data were gathered to complement the existing data compiled by Drenning (2021). The additional data collected through literature review include 18 pot studies and 34 field studies. The total studies included in the database (existing data plus additional data) is 121; of which pot studies is19% as can be seen in Figure 4-1.

SUMMARY OF STUDIES INCLUDED IN THE DATABASE

Pot Studies ---- 19

Field Studies --- 98

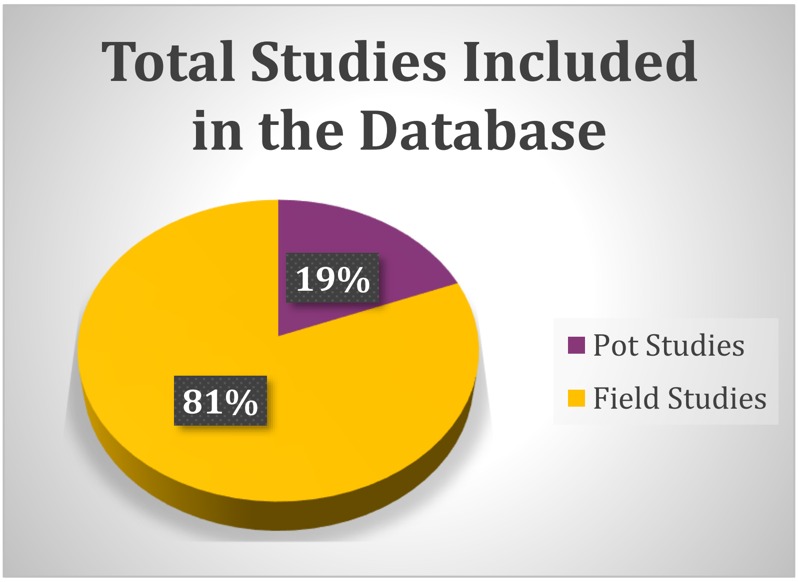


Figure 4-1: Proportion of studies included in the database in terms of pot and field studies.

4.2 Data Gathered from Mini Survey

Out of the 28 survey forms sent out, 19 respondents returned the forms with all required fields filled representing 67.8%. Of the 19 respondents, 6 (31.6%) confirmed using phytoremediation or natural based solution (NBS) in their remediation projects while all respondents (100%) confirmed working with contaminated sites with three years being the least duration spent working with contaminated sites. In Table 4-1 and Table 4-2, the data gathered from the respondents are collated and summarized while in Table 4-3Table 4-3, the statistics about the practice of phytoremediation in Sweden are presented.

Table 4-1: Survey Results – List of questions that a database could answer according to stakeholders / experts.

Suitable Data for a Database
Type of contaminant
Climate zone
Type of plants
Cost of remediation
Duration of remediation
Amendment / Enhancement
Site conditions
Root depth
Types of phyto-technologies
Soil classification
Examples of phytoremediation Projects
Planting density
Types and cost of maintenance
How much biomass is produced
CO2 footprint

Table 4-2: : Survey Results – List of suitable data to be included in a database according to stakeholders / experts.

Typical Questions a Database Could Answer
What is the end use of the plants harvested?
Can the site be used for other purposes while remediation is ongoing?
What is the accumulation rate of the plants?
What are existing or past projects?
How can we overcome uncertainties and convince authorities?
What maintenance do I need throughout the lifespan of the project?
What is public perception of phytoremediation?
Can combination with traditional methods produce desire results?
What are the risk objects / pathways
What are the growing conditions?
What is the cost of remediation?
What are the operational conditions?

Table 4-3: Statistics of the practice of Phytoremediation in Sweden.

Respondent	Role of Respondent	How long have you worked with contaminated sites?	Have you used phytoremediation or other nature-based solution for soil or water remediation?
1	Landscape architect / Partner	9	No
2	Researcher and owner of phytoremediation company	31	Yes
3	Project Manager	30	No
4	Senior environmental consultant	15	No
5	Environmental Strategist	4	No
6	Project Leader	8	Yes
7	Project leader in research projects and supervisor PhD students	19	Yes
8	Planner of Public Places	3	No
9	Environmental Consultant, Project manager	15	No
10	Researcher	N/A	Yes
11	Remediation Expert	26	N/A
12	Head of department, Investigator of contaminated Sites	21	No
13	Specialist, Contaminated Sites	N/A	No
14	Soil Environment Specialist	13	No
15	Research and Development	20+	No
16	Researcher	>20	Yes
17	Environmental Engineer	6	No
18	Contaminated Sites Specialist	8	No
19	Researcher	5	Yes

4.3 The Database

4.3.1 Layout of the Database

The database is built on an excel spreadsheet which is available to all users once they have access to a Microsoft package. The decision to use excel was based on the following considerations: i) the audience/user of the database is anyone desiring to practice phytoremediation, regardless of whether the user is a practitioner, researcher, or a non-practitioner. Therefore, it is appropriate to use a software that does not require additional charges, besides subscription to Microsoft package; and ii) the database is developed to preserve data that will be use from time to time by practitioners. Therefore, it was deemed necessary to use a software preserving data for a long time without requiring the need for maintenance. The database was constructed using macros, advanced filters' function and visual basic for applications (VBA). The combination of these excel features enhances the functionality of the database.

The database consists of four excel sheets which include i) *the development sheet; ii) the guide sheet; ii) the database sheet; and iv) the filter list sheet*. The database and the development sheets are hidden can be accessed by unhiding the sheets. The database contains several searchable interconnected data indexes classified into *location, type of study, scientific and common names of plants, contaminant name, contaminant group, contaminant classification, phyto-technologies, general and specific climatic zones, type of study, and full reference to the original studies*. Also included into the database are non-searchable columns such as amendments, notes, and year of study. Figure 4-2 depicts the structure of the database.

The data indexes are categorized under the following headings:

Location and continent: provide the country in which the studies were conducted. This is important because it allows user to verify climatic zone of the study site, for example.

Type of study: indicating the type of study distinguishes field study from pot studies. It is important to extricate pot studies from field studies when investigating existing/published studies to compare with your site, because results from field studies more relevant than pot studies. Pot studies are usually done in spike soils, (and with newly contaminated soil) under optimal climatic conditions. For this reason, the results from pot studies are not always demonstrated under field conditions, where the soil might have been contaminated for a long time.

Plant species: classified under two different headings: scientific name and common name. this is necessary as it provides opportunity for non-scientific users of the database to easily recognize plant species of their choice using the common name.

Contaminant name: lists names of all the contaminants contained in the database, i.e., As, Cd, Pb, Hg, etc. By selecting a particular contaminant, the user narrows down his/her search.

Contaminant Group: provides the group a particular contaminant belongs to. For example, Cd belongs to the metal group of contaminants.

Contaminant Classification: categorizes the contaminants into organic and inorganic. It is important to know the classification a particular contaminant falls in because this helps in planning remediation projects.

Phyto-technologies: this category contains the phytoremediation technology / technique that was applied. When more than one technology was applied in a single study, they are reported separately, thus each having its own row.

Climatic zones: to be clearer and reduce uncertainties of the climatic condition under which the study was conducted, the database contains general and specific climatic zones. This will help users to narrow down their search. The definitions of climatic zones are presented in Table 3-2. Each of climatic zone codes has criteria which the describe the temperature ranges, rainfall, and annual precipitation (Kottek et al., 2006; The GLOBE Program, 2000)

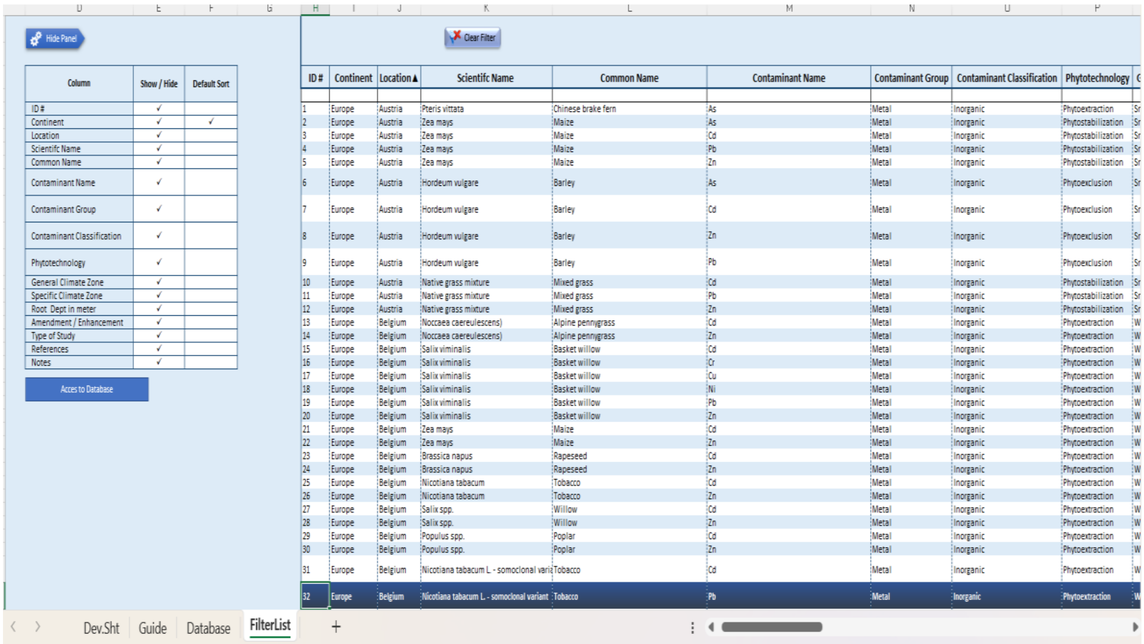


Figure 4-2: Layout of the database.

4.3.2 Data Entry Form

The "**Data Entry Form**" allows users to enter new data into the database. It can be accessed by clicking the "*Enter New Data*" button on the filter list sheet (see Figure 4-2). When all the fields are filled out and saved, the immediate last row in the database is populated. Depending on the design of the study, multiple rows may be populated from a single study. For example, if a study involves more than one contaminant, each of the studied contaminants will be reported separately into the database (one row per contaminant) and this is the same case with studies involving multiple species and technologies. Upon opening the "*Data Entry Form", user clicks on the "*Add New Data*" button (Shown Figure 4-3) to prepare the form for data entry. After entry all data, the user clicks the "*Save Data*" button (Shown in Figure 4-4). When the" Save *Data*" button is clicked, the user is presented with a popup message cautioning for proper data entry. The data is saved to the database by choosing the "Yes" option while the "No" option allows users to edit the entries (See Figure 4-4). It is important that user checks all entries before saving the data because it is not possible to make changes to the data once saved.

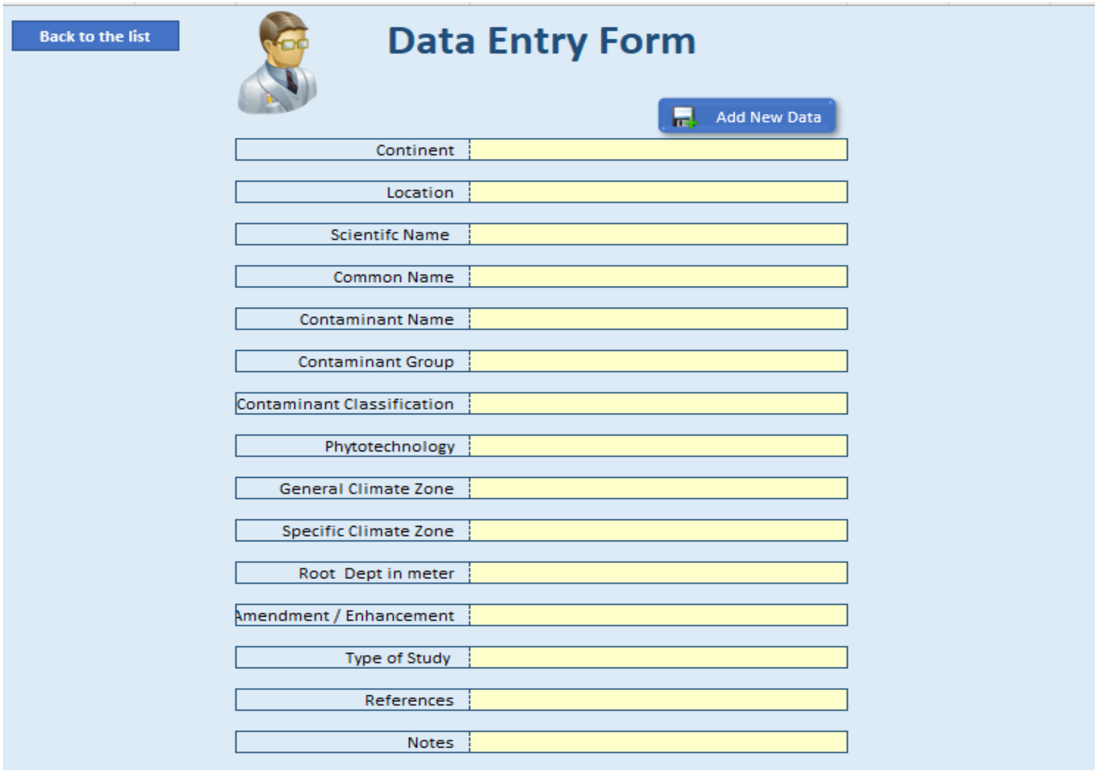


Figure 4-3: Data Entry Form – screen 1.

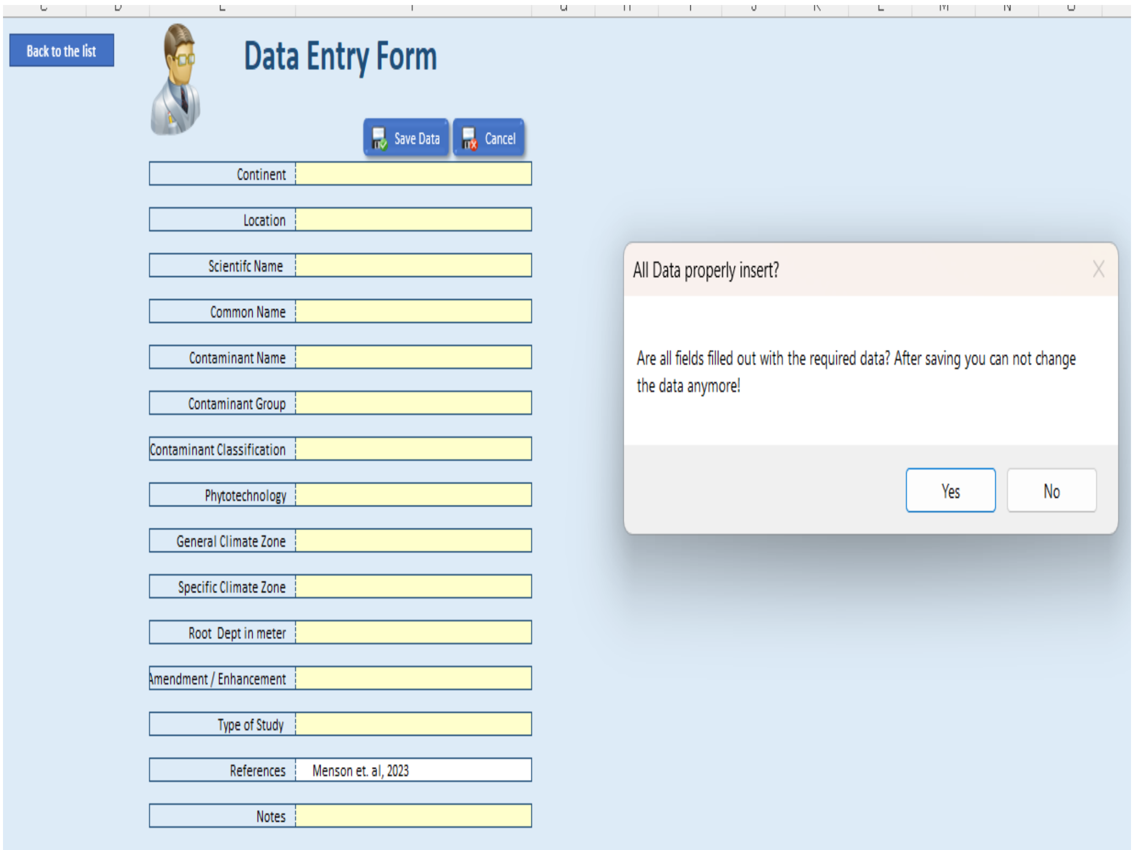


Figure 4-4: Data Entry Form – screen 2.

4.3.3 Stakeholders / Experts Feedback

After the short online workshop, in which a demonstration of the database was conducted, the database was discussed. During the discussion, the stakeholders /experts provided their feedback on the functionality, overall structure and the relevance of the data included in the database. The feedback was summarized and presented in Table 4-4.

Table 4-4: Feedback from workshop and action taken.

FEATURE	FEEDBACK	ACTION TAKEN
Functionality	Provide explanations of climatic zones criteria such as temperature ranges	A link to temperature ranges was added in the Guide Sheet
	Create easy way for user to either copy the link into the browser or follow the link by clicking	full link addresses of the references were inserted which allows clicking
	Provide explanation about how to use the data entry form	A detailed explanation was provided in the Guide Sheet
	Provide explanation about how to enable macros	A step-by-step explanation was provided in the Guide Sheet
Data Relevance	It is necessary to include information about the end use of the biomass from phytoextraction	This was recommended for the future as there was no time to do this
	Provide explanation on the outcome of studies, i.e,. was it successful?	The outcome of the studies was provided in the “Notes Column”
Overall Structure of Database	Provide explanation about how to manage the database	Proposal for proper management of database is provided
	Inclusion of data entry tracking feature	Proposed for the future

4.3.4 How to use the Database

Upon opening the database, the user will be presented with the guide sheet which contains all the instructions of using the database. It is recommended that the user read the instructions (presented in Appendix A) before attempting to use the database. Data search is done on the filter list sheet. To search for data, the user can go at the top of each column and type the information they are interested in, alternatively user can select the information from the dropdown list at the top of each column. User can narrow down their search by selecting multiple search criteria. The filter list sheet has four buttons, ***customize table, hide panel, clear filter, and enter new data***. Clicking the “*customize table*” button presents the user with a table with the option to decide what information is displayed. When the “*hide panel*” button is clicked, the customize table disappears. Clicking the “*enter new data*” button will lead the user to a data entry form (discussed in section 4.4.2) which allows for entry of new data onto the database. The “*clear filter*” button resets the database to default. When the database is reset, the “*filter data*” button disappears until the user starts to enter new search criteria. The detailed instructions on how to use the database is presented in Appendix A.

5 Discussion

The database is developed to assist practitioners and researchers in planning their phytoremediation projects. The database is created using a simple and available software (excel) to allow non-scientific users such as landowners, farmers, facility workers, gardeners etc. However, it is not recommended to plan your phytoremediation project on the sole basis of the data gathered from the database. Users are advised to use the links provided to gather more detailed information about the studies and the climatic zones. For example, the database only provides estimated climatic zones of the study sites but does not give the variables driving the climate of the site. When the user visits the original report, he/she can gather information such as annual precipitation, evaporation, the growing seasons, and a general description of the site and with this detailed information, he/she can better plan their projects.

A user may consult the database, for example, after investigating and characterizing their sites. This way, he/she already have an idea of the type of contaminants and the climatic conditions. With this initial information, he/she can now consult the database to look up studies that were done on sites with similar characteristics. The information gathered from the database will then serve as a starting point for planning his/her phytoremediation project.

5.1 Data Included in the Database

To complement existing data gathered and compiled by Paul Drenning in his study (Drenning, 2021), additional data were gathered through literature review from existing and published pot and field studies in phytoremediation. The studies are from Europe, North America, Asia, Africa, and Australia with majority of the studies being from Europe. From the data gathered, it can be said that the practice of phytoremediation is gaining attention in Europe and North America followed by Asia.

Most of the studies from Europe were conducted as part of the European GREENLAND project which targeted eight (8) European countries and the EU Life Program demonstration project under the banner “Biomass, Remediation, re-Generation” (BioReGen) which aimed at Reusing Brownfield sites for Renewable Energy Crops (Lord, 2015; Quintela-Sabarís et al., 2017). The studies in the European Union typically consisted of phytoextraction implemented in Belgium, Sweden, Germany, and Switzerland, aided phytoextraction in France, and aided phytostabilization or phytoexclusion in Poland, France, and Austria (Kumpiene et al., 2014). Majority of the studies focused on the remediation of inorganic contaminants such as heavy metal. Studies on organic contaminants were conducted in Belgium, France, Germany, and Italy in addition to the inorganic contaminants.

In North America, only studies from the United States of America (USA) and Canada were reviewed. Except one study in the USA which focused on As, Pb and Zn (Gil-Loaiza et al., 2016) , all of the studies reviewed in North America were on remediation of organics, thus focusing on phytodegradation and rhizodegradation.

In Asia, data were gathered from studies in China, India, Pakistan, and Thailand. All Asian studies reviewed were conducted for the remediation of inorganics using phytoextraction. In China, the ability of the *Chinese brake fern* to remediate As, Cd, and Pb was investigated in a field study (Wan et al., 2016), In India, heavy metals remediation was investigated using *Tagetes patala and Tagetes* erecta (Biswal et al., 2022) while in Pakistan and Thailand, the studies focused on lead, chromium and arsenic (Bareen & Tahira, 2011).

In Africa, the remediation of crude oil and spent lubricating oil, using phytodegradation and rhizodegradation, were investigated in pot studies (Adongbede & Odogu, 2009). This could probably be because of the oil extraction activities in Nigeria.

In Australia, only one study was reviewed where the remediation of nickel was investigated using Berkheya coddii in New Zealand (Brooks et al., 2001).

It is important to distinguish field studies from pot studies. Pot studies do not always reveal what happens at field level; they either overestimate plant's ability to hyperaccumulate or change plant response to metal toxicity (Muratova et al., 2008). However, pot study is an important method of verifying the ability of plant species to remediate contaminants. Most pot study results are used to select suitable plant species to be used in field studies. For example, in their study Muratova et al. (2008) conducted pot study to select suitable plant species to be used in field trial of oil-sludge contaminated soil. Also in the study of an in situ application of activated carbon and biochar to PCB-contaminated soil, Denyes et al. (2013) found out that there were no significant differences between the GAC (granular activated carbon), Burt's biochar and Blue Leaf biochar treatments in either tissue type, which suggests that all carbon amendments performed equally in suppressing PCB phytoavailability; but when this experiment was replicated in a greenhouse setting, the results were quite different with only the GAC amendment significantly reducing the PCB uptake into *C. pepo* root tissue.

From the different studies reviewed, it is reported that plants performance can be enhanced by several methods. Even with well selected plants, there may still be uncertainties about the efficiency of phytoremediation technologies. To overcome these uncertainties and improve the success of phytoremediation, a combination of aids such as natural and chemical amendments, genetic engineering, and microbial stimulations, plays crucial role (Kafle et al., 2022). Phytoremediation strategies can be enhanced by 1) plants species especially adapted to grow in the contaminated site (this could be hyperaccumulators, local plants, or transgenic plants); 2) endophytic bacteria to enhance the degradation in the rhizosphere; 3) soil amendments to increase the contaminants bioavailability (using chelating agents and bio-surfactants); 4) soil fertilization to enhance the plant growth and microbial activity in the soil; and 5) coupling phytoremediation with other remediation technologies such as electrokinetic remediation or enhanced biodegradation in the rhizosphere (Kafle et al., 2022).

5.2 Management of the Database

For the database to serve the purpose for which it was developed, it must be managed efficiently. The management includes tracking data entry into the database and how often it is being used by practitioners. The management team should ensure that the data entered into the database are assessed against certain criteria to guarantee data quality thus increasing confidence in the database. The idea is to have the database in a particular location (platform) where it is accessed by users as opposed to have each user downloading and entering data at their own discretion. That way, data entry can be easily tracked. As the database is being used, there will be more functionality issues raised by users, the management team should be able to receive feedback from users and propose measures for improvements.

5.2.1 Limitations of the Database

While the database contains a collection of existing and published pilot and field studies, it has some drawbacks that the user is cautioned to observe:

- The data included into database is only a summary of the study results, therefore, users are strongly advised to visit the original reports following the links provided.
- The climatic zones reported in the database were estimated using the Koppen-Geiger climate map (Kottek et al., 2006), therefore, there may be some slight difference in specific climatic zones. Users are urged to visit the original reports where the authors explained the prevailing climatic conditions under which the studies were conducted.
- The database does not contain information such as remediation duration and cost of remediation since such information is site dependent.
- One of the feedback items from stakeholders is to add explanation about the end-use of the biomass from phytoremediation. This was not implemented due to time.
- As it is now, any user can download the database and enter data at their own discretion. The database does not contain data entry tracking feature, therefore data entered into the database cannot be tracked.

6 Conclusion and Recommendations

6.1 Conclusion

Phytoremediation is an emerging and promising technology for the remediation of contaminated sites. It has been perceived as being eco-friendly and cost-effective, thus offering an alternative to conventional methods which involve the use of heavy equipment and costly setups (Zodrow, 1999). However, more studies are required to investigate and substantiate the processes and benefits of phytoremediation. Among other factors, the choice of plants plays a pivotal role in the efficiency of phytoremediation. There are substantial studies including pot and field studies around world about plants potential in phytoremediation. The results from these studies can increase the knowledge about phytoremediation thereby promoting its application. Unfortunately, the study results are not always easily accessible (Gerhardt et al., 2017). In this master thesis, a searchable database, containing data from pilot and field studies, was developed, and can be used as a tool to support plant selection during phytoremediation project planning.

From the work performed throughout this project, few conclusions can be made as outlined below:

- Making study results more accessible to practitioners is an appropriate way of increasing knowledge about phytoremediation. This was supported by the collaboration with the stakeholders and practitioners, most of whom saw the development of searchable database as a valuable way of promoting phytoremediation.

- There is a lot of ongoing research around the world to study the potential of plant species in phytoremediation, but most of these studies are being reported in scientific articles.

- Though pot studies have limitations in terms of manifesting obtained results under field conditions, they are however, good way of assessing the potential of plant species to be used in field trials. Therefore, the database could be extended by adding more data from pot studies.

- Excel is a powerful tool that can be used to develop more advanced databases with high functionality. With the combination of advanced filter functions, visual basic for applications (VBA) and Macros, excel can perform more sophisticated searches.

6.2 Recommendation

To achieve the purpose for which the database is created, the following recommendations are cardinal.

- The database should be further developed to add more features such as cloud-based data storage, user login details, and data entry trackers.

- A management team / or web platform should be put into place and charge with the responsibility of the full management of the database.

- A study on how phytoremediation can gain more attention in Sweden should be conducted. The study should include a broader survey to incorporate more practitioners and researchers in Sweden to collect their views on how phytoremediation can get the needed attention from stakeholders, including central government.

7 REFERENCES

Adongbede, E., & Odogu, G. (2009). *Screening of Four Common Nigerian Weeds for Use in Phytoremediation of Soil Contaminated with Spent Lubricating Oil Antimicrobial activity of wild mushrooms View project*. http://www.academicjournals.org/AJPS

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals-Concepts and applications. In *Chemosphere* (Vol. 91, Issue 7, pp. 869–881). Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2013.01.075

Alkorta, I., Becerril, J., Garbisu, C., & Garbisu, C. (2010). Phytostabilization of Metal Contaminated Soils. *Reviews on Environmental Health*, *25*(2).

Aprill, W., & Sims, R. C. (1990). Evaluation of the use of prairie grasses for stimulating polycyclic aromatic hydrocarbon treatment in soil. In *Chemosphere* (Vol. 20, Issue 2).

Arthur, E. L., Rice, P. J. R., Rice, P. J. R., Anderson, T. A. A., Baladi, S. M., Henderson, K. L., & Coats, J. R. (2005). Phytoremediation—an overview. *Critical Reviews in Plant Sciences*, *24*(2), 109–122.

Asgari Lajayer, B., Khadem Moghadam, N., Maghsoodi, M. R., Ghorbanpour, M., & Kariman, K. (2019). Phytoextraction of heavy metals from contaminated soil, water and atmosphere using ornamental plants: mechanisms and efficiency improvement strategies. In *Environmental Science and Pollution Research* (Vol. 26, Issue 9, pp. 8468–8484). Springer Verlag. https://doi.org/10.1007/s11356-019-04241-y

Azadpour, A., & Matthews, J. E. (1996). Remediation of metal-contaminated sites using plants. *Remediation*, *6*(3), 1–18. https://doi.org/10.1002/rem.3440060302

Bareen, F. e., & Tahira, S. A. (2011). Metal accumulation potential of wild plants in tannery effluent contaminated soil of Kasur, Pakistan: Field trials for toxic metal cleanup using Suaeda fruticosa. *Journal of Hazardous Materials*, *186*(1), 443–450. https://doi.org/10.1016/j.jhazmat.2010.11.022

Barlow, R., Bryant, N., Andersland, J., & Sahi, S. (2000). Lead hyperaccumulation by sesbania drummondii. *Lead Hyperaccumulation by Sesbania Drummondii*, 112–114.

Bateman, A., Martin, M. J., O'Donovan, C., Magrane, M., Apweiler, R., Alpi, E., Antunes, R., Arganiska, J., Bely, B., Bingley, M., Bonilla, C., Britto, R., Bursteinas, B., Chavali, G., Cibrian-Uhalte, E., Da Silva, A., De Giorgi, M., Dogan, T., Fazzini, F., … Zhang, J. (2015). UniProt: A hub for protein information. *Nucleic Acids Research*, *43*(D1), D204–D212. https://doi.org/10.1093/nar/gku989

Beath, O. A. , H. F. E., & Gilbert, C. S. (1937). Selenium distribution in and seasonal variation of type vegetation occurring on seleniferous soils. *The Journal of the American Pharmaceutical Association*, *26*(5), 394–405.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future köppen-geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*. https://doi.org/10.1038/sdata.2018.214

Berman, H. M., Westbrook, J., Feng, Z., Gilliland, G., Bhat, T. N., Weissig, H., Shindyalov, I. N., & Bourne, P. E. (2000). The Protein Data Bank. In *Nucleic Acids Research* (Vol. 28, Issue 1). http://www.rcsb.org/pdb/status.html

Biswal, B., Singh, S. K., Patra, A., & Mohapatra, K. K. (2022). Evaluation of phytoremediation capability of French marigold (Tagetes patula) and African marigold (Tagetes erecta) under heavy metals contaminated soils. *International Journal of Phytoremediation*, *24*(9), 945–954. https://doi.org/10.1080/15226514.2021.1985960

Boros, M.-N., Micle, V., Lazăr, F., & SUR, I. M. (2016). Phytoremediation planning in the case of former industrial sites. In C. ROŞU, C. BACIU, C. COSMA, L. MUNTEAN, A. OZUNU, & D. RISTOIU (Eds.), *Studia ubb ambientum: Vols. 61 (1-2)* (pp. 5–14).

Brooks, R. R., Lee, J., Reeves, R. D., & Jaffre, T. (1977). Detection of nickeliferous rocks by analysis of herbarium specimens of indicator plants. *Journal of Geochemical Exploration*, *7*, 49–57.

Brooks, R. R., Robinson, B. H., Howes, A. W., & Chiarucci, A. (2001). An evaluation of Berkheya coddii Roessler and Alyssum bertolonii Desv. for phytoremediation and phytomining of nickel. *South African Journal of Science*, *97*(No. 11), 558–560.

Chang, C., & Hogland, W. (2022). Phytoremediation development in Sweden. *IOP Conference Series: Earth and Environmental Science*, *1096*(1). https://doi.org/10.1088/1755-1315/1096/1/012001

Chen, W., & Li, H. (2018). Cost-Effectiveness Analysis for Soil Heavy Metal Contamination Treatments. In *Water, Air, and Soil Pollution* (Vol. 229, Issue 4). Springer International Publishing. https://doi.org/10.1007/s11270-018-3784-3

Chirakkara, R. A., Cameselle, C., & Reddy, K. R. (2016). Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. In *Reviews in Environmental Science and Biotechnology* (Vol. 15, Issue 2, pp. 299–326). Springer Netherlands. https://doi.org/10.1007/s11157-016-9391-0

Choudhary, D. K., Sharma, A. K., Agarwal, P., Varma, A., & Tuteja, N. (2017). Volatiles and food security: Role of volatiles in agro-ecosystems. In *Volatiles and Food Security: Role of Volatiles in Agro-Ecosystems*. Springer Singapore. https://doi.org/10.1007/978-981-10-5553-9

Compernolle, T., van Passel, S., Weyens, N., Vangronsveld, J., Lebbe, L., & Thewys, T. (2012). Groundwater remediation and the cost effectiveness of phytoremediation. *International Journal of Phytoremediation*, *14*(9), 861–877. https://doi.org/10.1080/15226514.2011.628879

Cook, R. L., & Hesterberg, D. (2013). Comparison of Trees and Grasses for Rhizoremediation of Petroleum Hydrocarbons. *International Journal of Phytoremediation*, *15*(9), 844–860. https://doi.org/10.1080/15226514.2012.760518

Costello, M. J. (2009). Motivating online publication of data. In *BioScience* (Vol. 59, Issue 5, pp. 418–427). https://doi.org/10.1525/bio.2009.59.5.9

Cristaldi, A., Conti, G. O., Jho, E. H., Zuccarello, P., Grasso, A., Copat, C., & Ferrante, M. (2017). Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. In *Environmental Technology and Innovation* (Vol. 8, pp. 309–326). Elsevier B.V. https://doi.org/10.1016/j.eti.2017.08.002

Cundy, A. B., Bardos, R. P., Puschenreiter, M., Mench, M., Bert, V., Friesl-Hanl, W., Müller, I., Li, X. N., Weyens, N., Witters, N., & Vangronsveld, J. (2016). Brownfields to green fields: Realising wider benefits from practical

contaminant phytomanagement strategies. *Journal of Environmental Management*, *184*, 67–77. https://doi.org/10.1016/j.jenvman.2016.03.028
Cundy, A., Bardos, P., Puschenreiter, M., Witters, N., Mench, M., Bert, V., Friesl-Hanl, W., Müller, I., Weyens, N., & Vangronsveld, J. (2015). Developing Effective Decision Support for the Application of "Gentle" Remediation Options: The GREENLAND Project. *Remediation*, *25*(3), 101–114. https://doi.org/10.1002/rem.21435
Cunningham, S. D., Anderson, T. A., Schwab, A. P., & Hsu, F. C. (1996). Phytoremediation of soils contaminated with organic pollutants. *Advances in Agronomy*, *56*, 56–114.
Curl, E. A., & Truelove, B. (1986). *The Rhizosphere* (D. F. R. Bommer, R. B. R. Sabey, F. C. G. W. Thomas, L. Y. Vaadia, J. L. D. Van Vleck, & Ithaca, Eds.; 1st ed., Vol. 15). Springer Science & Business Media.
Dec, J., & Bollag, J. -M. (1994). Use of plant material for the decontamination of water polluted with phenols. *Biotechnology and Bioengineering*, *44*(9), 1132–1139. https://doi.org/10.1002/bit.260440915
Deng, Z., & Cao, L. (2017). Fungal endophytes and their interactions with plants in phytoremediation: A review. In *Chemosphere* (Vol. 168, pp. 1100–1106). Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2016.10.097
Denyes, M. J., Rutter, A., & Zeeb, B. A. (2013). In situ application of activated carbon and biochar to PCB-contaminated soil and the effects of mixing regime. *Environmental Pollution*, *182*, 201–208. https://doi.org/10.1016/j.envpol.2013.07.016
Drenning, P. (2021). *Gentle Remediation Options (GRO): A Literature Review (Part 1/2) Phd Project (ECO-GRO)-Enhancing Ecosystem Services by innovative remediation using Gentle Remediation Options*. https://doi.org/10.13140/RG.2.2.36086.11849
Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, vonne, & Norrman, J. (2022). A risk management framework for Gentle Remediation Options (GRO). *Science of the Total Environment*, *802*, 149880.
Ely, C. S., & Smets, B. F. (2017). Bacteria from wheat and cucurbit plant roots metabolize PAHs and aromatic root exudates: Implications for rhizodegradation. *International Journal of Phytoremediation*, *19*(10), 877–883. https://doi.org/10.1080/15226514.2017.1303805
Etim, E., & Etim, E. E. (2012). Thermodynamic properties of Interstellar Medium (ISM) View project Phytoremediation and Its Mechanisms: A Review. *International Journal of Environment and Bioenergy*, *2012*(3), 120–136. https://www.researchgate.net/publication/312443920
Famulari, S., & Witz, K. (2015). A User-Friendly Phytoremediation Database: Creating the Searchable Database, the Users, and the Broader Implications. *International Journal of Phytoremediation*, *17*(8), 737–744. https://doi.org/10.1080/15226514.2014.987369
Farraji, H., Zaman, N. Q., Tajuddin, R. M., & Faraji, H. (2016). Advantages and disadvantages of phytoremediation: A concise review. *International Journal for Environmental and Technological Sciences*, *2*, 69–75.
Farrell, R. E., Frick, C. M., Germida, J. J., Godwin, B., & Thorpe, J. (2000). *PhytoPet: A database of plants that play a role in the phytoremediation of petroleum hydrocarbons*. *37*(19).

Favas, P. J., Pratas, J., Varun, M., D'Souza, R., & Paul, M. S. (2014). Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora. In *Environmental risk assessment of soil contamination* (Vol. 3, pp. 485–516).
Federle, T. W., & Burney, S. S. (1989). Mineralization of Surfactants by Microbiota of Aquatic Plants. *Applied and Environmental Microbiology*, *55*(8), 2092–2094.
Fulekar, M. H., & Pathak, B. (2012). Rhizofiltration: a green technology for remediation of heavy metals. *International Journal of Innovations in Bio-Sciences*, *2*(4), 193–199. http://www.parees.co.in/ijibs.htm
Garrison, A. W., Nzengung, V. A., Avants, J. K., Ellington, J. J., Jones, W. J., Rennels, D., & Wolfe, N. L. (2000). Phytodegradation of p,p'-DDT and the enantiomers of o,p'-DDT. *Environmental Science and Technology*, *34*(9), 1663–1670. https://doi.org/10.1021/es990265h
Gatliff, E. G. (1994). Vegetative remediation process offers advantages over traditional pump-and-treat technologies. *Remediation Journal*, *4*(3), 343–352. https://doi.org/10.1002/rem.3440040307
Gerhardt, K. E., Gerwing, P. D., & Greenberg, B. M. (2017). Opinion: Taking phytoremediation from proven technology to accepted practice. In *Plant Science* (Vol. 256, pp. 170–185). Elsevier Ireland Ltd. https://doi.org/10.1016/j.plantsci.2016.11.016
Ghaly, A. E., Kamal, M., & Mahmoud, N. S. (2005). Phytoremediation of aquaculture wastewater for water recycling and production of fish feed. *Environment International*, *31*(1), 1–13. https://doi.org/10.1016/j.envint.2004.05.011
Gillespie, L. D., & Gillespie, W. J. (2003). Finding Current Evidence: Search Strategies and Common Databases. *Clinical Orthopaedics and Related Research*, *413*, 133–145. https://doi.org/10.1097/01.blo.0000079324.41006.dc
Gil-Loaiza, J., White, S. A., Root, R. A., Solís-Dominguez, F. A., Hammond, C. M., Chorover, J., & Maier, R. M. (2016). Phytostabilization of mine tailings using compost-assisted direct planting: Translating greenhouse results to the field. *Science of the Total Environment*, *565*, 451–461. https://doi.org/10.1016/j.scitotenv.2016.04.168
Gómez-Gutiérrez, A., Garnacho, E., Bayona, J. M., & Albaigés, J. (2007). Screening ecological risk assessment of persistent organic pollutants in Mediterranean sea sediments. *Environment International*, *33*(7), 867–876. https://doi.org/10.1016/j.envint.2007.04.002
Green, C., & Hoffnagle, A. (2004). *Phytoremediation field studies database for chlorinated solvents, pesticides, explosives, and metals*.
Guarino, F., Miranda, A., Castiglione, S., & Cicatelli, A. (2020). Arsenic phytovolatilization and epigenetic modifications in Arundo donax L. assisted by a PGPR consortium. *Chemosphere*, *251*. https://doi.org/10.1016/j.chemosphere.2020.126310
Gutiérrez-Ginés, M. J., Hernández, A. J., Pérez-Leblic, M. I., Pastor, J., & Vangronsveld, J. (2014). Phytoremediation of soils co-contaminated by organic compounds and heavy metals: Bioassays with Lupinus luteus L. and associated endophytic bacteria. *Journal of Environmental Management*, *143*, 197–207. https://doi.org/10.1016/j.jenvman.2014.04.028

Haagen-Smit, A. J., Darley, E. F., Zaitlin, M., Hull, H., & Noble, W. (1952). Investigation on injury to plants from air pollution in the Los Angeles area. *Plant Physiology*, *27*(1), 18–34.

Heiderscheidt, D. (2018). European History Commons, Nature and Society Relations Commons, Other History Commons, and the Physical and Environmental Geography Commons Recommended Citation Recommended Citation Heiderscheidt. In *Ursidae: The Undergraduate Research Journal at the University of Northern Colorado* (Vol. 7, Issue 3). https://digscholarship.unco.edu/urjAvailableat:https://digscholarship.unco.edu/urj/vol7/iss3/3

Ho-Man, L., Zhen-Wen, W., Zhi-Hong, Y., Kin-Lam, Y., Xiao-Ling, P., & Kwai-Chung, C. (2013). Interactions Between Arbuscular Mycorrhizae and Plants in Phytoremediation of Metal-Contaminated Soils: A Review * 1. In *Pedosphere* (Vol. 23, Issue 5).

Hong, M. S., Farmayan, W. F., Dortch, I. J., Chiang, C. Y., McMillan, S. K., & Schnoor, J. L. (2001). Phytoremediation of MTBE from a groundwater plume. *Environmental Science and Technology*, *35*(6), 1231–1239. https://doi.org/10.1021/es001911b

ITRC Phytotechnologies Team. (2009). *Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised*.

Jacklin, D. M., Brink, I. C., & Jacobs, S. M. (2021). A phyto-guide to species selection for optimized south african green infrastructure. *Water SA*, *47*(4), 515–522. https://doi.org/10.17159/WSA/2021.V47.I4.3875

Jadia, C. D., & Fulekar, M. H. (2009). Phytoremediation of heavy metals: Recent techniques. *African Journal of Biotechnology*, *8*(6), 921–928. http://www.academicjournals.org/AJB

Jain, S. K., Vasudevan, P., & Jha, N. K. (1989). Removal of some Heavy Metals from Polluted Water by Aquatic Plants: Studies on Duckweed and Water Velvet. In *Biological Wastes* (Vol. 28).

’Jones, A. K. ’, ’French, J. C. ’, & ’Pfaltz, J. L. ’. (1990). *Scientific Database Management*.

Jones, D. L., Williamson, K. L., & Owen, A. G. (2006). Phytoremediation of landfill leachate. *Waste Management*, *26*(8), 825–837. https://doi.org/10.1016/j.wasman.2005.06.014

Jordahl, J. L., Foster, L., Schnoor, J. L., & Alvarez, P. J. J. (1997). Effect of hybrid poplar trees on microbial populations important to hazardous waste bioremediation. *Environmental Toxicology and Chemistry*, *16*(6), 1318–1321. https://doi.org/10.1002/etc.5620160630

Kable, A. K., Pich, J., & Maslin-Prothero, S. E. (2012). A structured approach to documenting a search strategy for publication: A 12 step guideline for authors. *Nurse Education Today*, *32*(8), 878–886.

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, *8*, 100203.

Keller, C., Hammer, D., Kayser, A., Richner, W., Brodbeck, M., & Sennhauser, M. (2003). Root development and heavy metal phytoextraction efficiency: comparison of different plant species in the field. In *Plant and Soil* (Vol. 249).

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130
Kumpiene, J., Bert, V., Dimitriou, I., Eriksson, J., Friesl-Hanl, W., Galazka, R., Herzig, R., Janssen, J., Kidd, P., Mench, M., Müller, I., Neu, S., Oustriere, N., Puschenreiter, M., Renella, G., Roumier, P. H., Siebielec, G., Vangronsveld, J., & Manier, N. (2014). Selecting chemical and ecotoxicological test batteries for risk assessment of trace element-contaminated soils (phyto)managed by gentle remediation options (GRO). *Science of the Total Environment*, *496*, 510–522. https://doi.org/10.1016/j.scitotenv.2014.06.130
Li, J. T., Liao, B., Lan, C. Y., Ye, Z. H., Baker, A. J. M., & Shu, W. S. (2010). Cadmium Tolerance and Accumulation in Cultivars of a High-Biomass Tropical Tree (Averrhoa carambola) and Its Potential for Phytoextraction . *Journal of Environmental Quality*, *39*(4), 1262–1268. https://doi.org/10.2134/jeq2009.0195
Limmer, M., & Burken, J. (2016). Phytovolatilization of Organic Contaminants. In *Environmental Science and Technology* (Vol. 50, Issue 13, pp. 6632–6643). American Chemical Society. https://doi.org/10.1021/acs.est.5b04113
Lord, R. A. (2015). Reed canarygrass (Phalaris arundinacea) outperforms Miscanthus or willow on marginal soils, brownfield and non-agricultural sites for local, sustainable energy crop production. *Biomass and Bioenergy*, *78*, 110–125. https://doi.org/10.1016/j.biombioe.2015.04.015
Meeson, B. W., & Strebel, D. E. (1998). The Publication Analogy: A Conceptual Framework for Scientific Information Systems. *Remote Sensing Reviews*, *16*(4), 255–292. https://doi.org/10.1080/02757259809532356
Mench, M., Lepp, N., Bert, V., Schwitzguébel, J. P., Gawronski, S. W., Schröder, P., & Vangronsveld, J. (2010). Successes and limitations of phytotechnologies at field scale: Outcomes, assessment and outlook from COST Action 859. In *Journal of Soils and Sediments* (Vol. 10, Issue 6, pp. 1039–1070). https://doi.org/10.1007/s11368-010-0190-x
Mendez, M. O., & Maier, R. M. (2008). Phytoremediation of mine tailings in temperate and arid environments. In *Reviews in Environmental Science and Biotechnology* (Vol. 7, Issue 1, pp. 47–59). https://doi.org/10.1007/s11157-007-9125-4
Merkl, N., Schultze-Kraft, R., & Infante, C. (2005). Assessment of tropical grasses and legumes for phytoremediation of petroleum-contaminated soils. *Water, Air, and Soil Pollution*, *165*, 195–209.
Miller, R. R. (1996). *Phytoremediation, technology overview report*.
Mohajan, H. K. (2019). *The First Industrial Revolution: Creation of a New Global Human Era*. *5*(No. 4), 377–387.
Mohajan, H. K. (2020). *The Second Industrial Revolution has Brought Modern Social and Economic Developments*. *6*(No. 1), 1–14.
Muratova, A. Y., Dmitrieva, T. V., Panchenko, L. V., & Turkovskaya, O. V. (2008). Phytoremediation of oil-sludge-contaminated soil. *International Journal of Phytoremediation*, *10*(6), 486–502. https://doi.org/10.1080/15226510802114920
Muthusaravanan, S., Sivarajasekar, N., Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., Gayathri, V., & Al-Duaij, O. K. (2018). Phytoremediation of heavy metals: mechanisms, methods and enhancements. In *Environmental*

Chemistry Letters (Vol. 16, Issue 4, pp. 1339–1359). Springer Verlag. https://doi.org/10.1007/s10311-018-0762-3

Nagendran, R., Selvam, A., Joseph, K., & Chiemchaisri, C. (2006). Phytoremediation and rehabilitation of municipal solid waste landfills and dumpsites: A brief review. *Waste Management*, *26*(12), 1357–1369. https://doi.org/10.1016/j.wasman.2006.05.003

Narayanan, M., Davis, L. C., & Erickson, L. E. (1995). Fate of Volatile Chlorinated Organic Compounds in a Laboratory Chamber with Alfalfa Plants. *Environmental Science & Technology*, *29*(9), 2437–2444.

Nietch, C. T., Morris, J. T., & Vroblesky, D. A. (1999). Biophysical mechanisms of trichloroethene uptake and loss in baldcypress growing in shallow contaminated groundwater. *Environmental Science and Technology*, *33*(17), 2899–2904. https://doi.org/10.1021/es981183g

Nikolić, M., & Stevović, S. (2015). Family Asteraceae as a sustainable planning tool in phytoremediation and its relevance in urban areas. In *Urban Forestry and Urban Greening* (Vol. 14, Issue 4, pp. 782–789). Elsevier GmbH. https://doi.org/10.1016/j.ufug.2015.08.002

Nyer, E. K., & Gatliff, E. G. (1996). Phytoremediation. *Groundwater Monitoring & Remediation*, *16*(1), 58–62. https://doi.org/10.1111/j.1745-6592.1996.tb00569.x

Porter, J. H. (2018). Scientific Databases for Environmental Research. In F. Recknagel & W. K. Michener (Eds.), *Ecological Informatics: Data Management and Knowledge Discovery* (3rd ed., pp. 27–53). Springer International Publishing AG.

Quintela-Sabarís, C., Marchand, L., Kidd, P. S., Friesl-Hanl, W., Puschenreiter, M., Kumpiene, J., Müller, I., Neu, S., Janssen, J., Vangronsveld, J., Dimitriou, I., Siebielec, G., Gałązka, R., Bert, V., Herzig, R., Cundy, A. B., Oustrière, N., Kolbas, A., Galland, W., & Mench, M. (2017). Assessing phytotoxicity of trace element-contaminated soils phytomanaged with gentle remediation options at ten European field trials. *Science of the Total Environment*, *599–600*, 1388–1398. https://doi.org/10.1016/j.scitotenv.2017.04.187

Reeves, R. D., Baker, A. J. M., Jaffré, T., Erskine, P. D., Echevarria, G., & van der Ent, A. (2018). A global database for plants that hyperaccumulate metal and metalloid trace elements. In *New Phytologist* (Vol. 218, Issue 2, pp. 407–411). Blackwell Publishing Ltd. https://doi.org/10.1111/nph.14907

Robinson, B., Fernández, J.-E., Madejón, P., Marañón, T., Murillo, J. M., Green, S., & Clothier, B. (2003). Phytoextraction: an assessment of biogeochemical and economic viability. In *Plant and Soil* (Vol. 249).

Salido, A. L., Hasty, K. L., Lim, J. M., & Butcher, D. J. (2003). Phytoremediation of arsenic and lead in contaminated soil using Chinese Brake ferns (Pteris vittata) and Indian mustard (Brassica juncea). *International Journal of Phytoremediation*, *5*(2), 89–103. https://doi.org/10.1080/713610173

Salt, D. E., Blaylock, M., PBA Kumar, N., Dushenkov, V., Ensley, B. D., Chet, H., & Raskin, llya. (1995). *Phytoremediation: A Novel Strategy for the Removal of Toxic Metals from the Environment Using Plants*. http://www.nature.com/naturebiotechnology

Sharma, S., & Pathak, H. (2014). Basic techniques of phytoremediation. *International Journal of Scientific & Engineering Research*, *5*(4). http://www.ijser.org

Singh, O. V., Labana, S., Pandey, G., Budhiraja, R., & Jain, R. K. (2003). Phytoremediation: an overview of metallic ion decontamination from soil. *Applied Microbiology and Biotechnology*, *61*(5–6), 405–412. https://doi.org/10.1007/s00253-003-1244-4

Stephenson, C., & Black, C. R. (2014). One step forward, two steps back: The evolution of phytoremediation into commercial technologies. In *Bioscience Horizons* (Vol. 7). Oxford University Press. https://doi.org/10.1093/biohorizons/hzu009

Stolberg, F., & Zadniprovska, A. (2007). Phytoremediation technologies applicable to aquatic requirement (an overview). *Linnaeus Eco-Tech*, 217–226. https://doi.org/10.15626/eco-tech.2007.020

Suresh, B., & Ravishankar, G. A. (2004). Phytoremediation - A novel and promising approach for environmental clean-up. In *Critical Reviews in Biotechnology* (Vol. 24, Issues 2–3, pp. 97–124). https://doi.org/10.1080/07388550490493627

Susarla, S., Medina, V. F., & Mccutcheon, S. C. (2002). Phytoremediation: An ecological solution to organic chemical contamination. In *Ecological Engineering* (Vol. 18). www.elsevier.com/locate/ecoleng

Thank, I., Atkin, D., Bogart, D., Boustan, L., Clay, K., Costa, D., Cummins, N., Fajgelbaum, P., Foquet, R., Guinnane, T., Kahn, M., Kung, E., Lafourcade, M., Lamoreaux, N., Lleras-Muney, A., Moser, P., Rothenberg, A., Troesken, W., & Hanlon, W. W. (1913). *Coal Smoke and the Costs of the Industrial Revolution*. http://www.nber.org/papers/w22921

The GLOBE Program. (2000). Köppen-Geiger Climate Classification Category Descriptions. *Climate Research Unit Timeseries (CRU TS 22.1) and VASClimO Precipitation Data*, *1*.

Tonelli, F. C. P., Tonelli, F. M. P., Lemos, M. S., & de Melo Nunes, N. A. (2022). Mechanisms of phytoremediation. In *Phytoremediation: Biotechnological Strategies for Promoting Invigorating Environs* (pp. 37–64). Elsevier. https://doi.org/10.1016/B978-0-323-89874-4.00023-6

’Tonelli, F. M. P., Bhat, R. A., Dar, G. H., & Hakeem, K. R. (2022). The history of phytoremediation. In *Phytoremediation* (pp. 1–18). Academic Press.

Vangronsveld, J., Herzig, R., Weyens, N., Boulet, J., Adriaensen, K., Ruttens, A., Thewys, T., Vassilev, A., Meers, E., Nehnevajova, E., van der Lelie, D., & Mench, M. (2009). Phytoremediation of contaminated soils and groundwater: Lessons from the field. *Environmental Science and Pollution Research*, *16*(7), 765–794. https://doi.org/10.1007/s11356-009-0213-6

Wan, X., Lei, M., & Chen, T. (2016). Cost–benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. *Science of the Total Environment*, *563–564*, 796–802. https://doi.org/10.1016/j.scitotenv.2015.12.080

Wang, H., Shan, X. Q., Wen, B., Zhang, S., & Wang, Z. J. (2004). Responses of antioxidative enzymes to accumulation of copper in a copper hyperaccumulator of Commoelina communis. *Archives of Environmental Contamination and Toxicology*, *47*(2), 185–192. https://doi.org/10.1007/s00244-004-2222-2

Wang, J., Song, X., Wang, Y., Bai, J., Li, M., Dong, G., Lin, F., Lv, Y., & Yan, D. (2017). Bioenergy generation and rhizodegradation as affected by microbial community distribution in a coupled constructed wetland-microbial fuel cell system associated with three macrophytes. *Science of the Total Environment*, *607–608*, 53–62. https://doi.org/10.1016/j.scitotenv.2017.06.243

Winquist, E., Björklöf, K., Schultz, E., Räsänen, M., Salonen, K., Anasonye, F., Cajthaml, T., Steffen, K. T., Jørgensen, K. S., & Tuomela, M. (2014). Bioremediation of PAH-contaminated soil with fungi - From laboratory to field scale. *International Biodeterioration and Biodegradation*, *86*, 238–247. https://doi.org/10.1016/j.ibiod.2013.09.012

Ya, N., & Ramachandra, T. V. (2006). Phytoremediation: processes and mechanisms. *Journal of Ecobiology*, *18*(1), 33–38.

Yin, H., Tan, Q., Chen, Y., Lv, G., He, D., & Hou, X. (2011). Polycyclic aromatic hydrocarbons (PAHs) pollution recorded in annual rings of gingko (Gingko biloba L.): Translocation, radial diffusion, degradation and modeling. *Microchemical Journal*, *97*(2), 131–137. https://doi.org/10.1016/j.microc.2010.08.004

Zhang, H., Dang, Z., Zheng, ; L C, & Yi, ; X Y. (2009). Remediation of soil co-contaminated with pyrene and cadmium by growing maize (Zea mays L.). *Int. J. Environ. Sci. Tech*, *6*(2), 249–258.

Zhou, W., & Qiu, B. (2005). Effects of cadmium hyperaccumulation on physiological characteristics of Sedum alfredii Hance (Crassulaceae). *Plant Science*, *169*(4), 737–745. https://doi.org/10.1016/j.plantsci.2005.05.030

Zodrow, J. J. (1999). Recent applications of phytoremediation technologies. *Remediation Journal*, *9*(2), 26–36.

8 APPENDIX A

INSTRUCTIONS FOR USING THE DATABASE	
FEATURE	**EXPLANATIONS**
Guide Sheet	The guide sheet contains the instructions / steps to follow when using this database. It is recommended that you read all the information on this sheet before proceeding to data search.
Filter List Sheet	This sheet allows users to search for data. The **FILTER LIST SHEET** contains four buttons which perform unique functions
Customize Table Button	When this button is pressed, a table, with all the headings in the main table will appears. This provides the user the opportunity to decide which information is displayed by ticking or unticking each of the listed headings
Hide Panel Button	This button only appears when the **CUSTOMIZE TABLE** button is clicked. Clicking the **HIDE PANEL** button will bring back the **CUSTOMIZE TABLE** button on your screen.
Clear Filter Button	The clear filter button resets the database to default. When the database is reset, the **CLEAR FILTER BUTTON** disappears until user starts to input new search criteria.
Enter New Data Button	Clicking this button will lead the user to the data entry form where new data can be added onto the database. It is highly recommended that all data are added onto the database via this form. Adding data via the main database is also possible but there is a possibility of destroying the database.
Data Sorting	Data in each column can be sorted according to the users' preference. This can be done by hovering the mouse over the heading of the column and clicking on the triangular shape that appears during the hovering.
Database Sheet	This sheet contains the data of all the studies that were reviewed. The **DATABASE SHEET** also contains some tables which can be accessed by scrolling to the far right of the database. These tables are used to develop the codes that are used in the development of this database. The **DATABASE SHEET** should not be accessed until the user decided to make some changes or upgrade the database.
Development Sheet	The **DEVELOPMENT SHEET,** like the **DATABASE SHEET**, contains supporting documents for the developing of the codes / macros.
How to enable Macros	The database contains macro; therefore, it is important to enable macro in order to use the database. Enabling macros via the "Trust Center" in excel does not always work. The recommended way to enable macro for this database is: right-click on the downloaded file (the database) and click on property. This will display a dialog box. The macro is then enabled by scrolling down to security and clicking on "Unblock".

DEPARTMENT OF ARCHITECTURE AND
CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY