

Contribution to studies on methods for cleaning up contaminated water and soil

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Abstract

In the current context, it is essential to understand the scale of the problem of soil and water contamination, and its implications for the environment and public health. This concern stems from the fact that soil and water are vital resources for life on Earth, and their contamination compromises not only the sustainability of ecosystems, but also the availability of essential resources for human beings. Water and soil contamination is complex and multifactorial.

The United Nations Environment Programme highlights this complexity by stating that "water and soil pollution result from multiple pressures, including urbanisation, intensive agriculture, industrialisation, climate change and conflict". There are scientific, technological, economic, political and ethical challenges involved. From a scientific point of view, understanding the transport and transformation of contaminants in soil and water, as well as their effects on human health and the environment, is crucial. It is therefore necessary to develop effective methods for detecting, analysing and decontaminating contaminated soil and water from a technological point of view.

Protecting and preserving water and soil resources is essential to ensure a sustainable future for future generations. To find sustainable solutions to preserve the quality of our water and soil resources, governments, international organisations, businesses and individuals must work together.

Keys Words: Phytoremediation, water, treatment, soil

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I. INTRODUCTION

Water and soil remediation or decontamination involves making the soil, subsoil, surface water and groundwater polluted by former waste deposits or by the infiltration of polluting substances, suitable for a new use (agricultural, residential or industrial) (Louba et al., 2014). The remediation of contaminated water and soil is a major challenge for public health and the environment. Pollutants from industrial, agricultural and urban activities can contaminate natural resources, requiring the application of effective clean-up methods to restore the quality of these environments.

According to the EPA, soil and groundwater contamination represents a significant risk to human health and the environment, and this statement underlines the crucial importance of treating contaminated areas to avoid harmful effects on ecosystems and public health. Industrial discharges, accidental spills, excessive use of fertilisers and pesticides in agriculture and urban run-off are just some of the many sources of soil and water contamination.

Remediation of contaminated water and soil is complex due to the variety of pollutants present, the geological and hydrological characteristics of contaminated sites, and the financial and technical challenges associated with clean-up operations. Removing pollution from contaminated water and soil requires an approach that integrates environmental sciences, chemistry, biology, geology, engineering and natural resource management (Gupta et al., 2012). It is complex because of the variety of pollutants (heavy metals, volatile organic compounds, pesticides, etc.) and the variety of geological and hydrological contexts. In his study of environmental remediation technologies, Dupont stresses that "the selection of a remediation method must be preceded by a thorough assessment of the specific characteristics of the contaminated site and the type and concentration of pollutants present". The effectiveness of interventions depends on this personalised approach. Methods for decontaminating contaminated water and soil can be physical, chemical, biological or a combination of the two. Depending on the type of pollution to be treated, the environmental context and the limits of the contaminated site, each of these methods has its advantages and disadvantages.

II. CLEAN-UP METHODS

2.1 Methods for cleaning up contaminated water Water pollution is a major threat to public health and the environment. According to the World Health.

2.2 billion people worldwide live without access to safe drinking water. This worrying situation highlights the crucial importance of techniques for depolluting contaminated water. Water purification is complex and multidimensional, as it can come from a variety of sources, such as industrial waste, domestic wastewater, agricultural chemicals and mining waste. Water contamination threatens not only human health but also aquatic biodiversity, reducing the availability of freshwater resources needed for human and ecological survival. To meet these crucial challenges, it is essential to identify and apply effective depollution techniques.

The decontamination of contaminated water is a crucial issue for the preservation of the environment and public health. Depollution methods aim to eliminate contaminants present in water, such as chemicals, heavy metals, pathogenic micro-organisms and other harmful substances. These methods can be physical, chemical or biological, and are essential to ensure the availability of clean, safe water for human consumption, as well as for the protection of aquatic ecosystems.

2.1.1 Physical treatment

Physical treatment of contaminated water is a process designed to remove pollutants and impurities from water using physical methods. This method includes processes such as filtration, sedimentation and adsorption on activated carbon. It aims to eliminate solid particles and certain chemical pollutants by physical means without chemically altering the water. Several techniques are used in the physical treatment of water, including:

1. Filtration: This involves passing water through a porous medium to remove suspended solids. Different types of filter can be used, such as sand filters, activated carbon filters, membrane filters, etc. Membrane filtration techniques are widely used in wastewater treatment plants (Saleh et al., 2020).

2. Settling: This method separates the heavier solid particles from the water by allowing them to settle to the bottom of the settling tank. The clarified water is then collected at the top of the tank.

3. Aeration: This consists of introducing air into the contaminated water, thereby promoting oxygenation and the elimination of certain pollutants. This can be done by agitating the water, using aeration devices or by letting the water run over a surface exposed to the air.

4. Coagulation/flocculation: This method involves adding chemicals, such as coagulants and flocculants, to the contaminated water. These chemicals react with the particles in suspension, forming larger aggregates called flocs, which make it easier to separate them from the water.

5. Ozonation: Ozonation is the process of treating water with ozone. Ozone, an unstable oxygen-rich gas, is used to oxidise and break down organic pollutants present in contaminated water. These physical methods can be used individually or in combination to achieve more effective purification of contaminated water. However, it is important to note that the choice of treatment methods depends on the types and concentration of pollutants present in the water to be treated. It is advisable to consult water treatment experts to determine the best approach for a specific case.

2.1.2 Chemical treatment

Chemical treatment of wastewater uses a number of chemical reactions to convert contaminants into safer chemicals. Coagulation and advanced oxidation processes (AOP), including ozonation and Fenton treatment, are the main chemical methods. Photocatalysis and membrane techniques are often used with chemical treatments (Saleh et al., 2020). This involves adding chemical substances to eliminate or neutralise pollutants. For example, ozonation and chlorination are used to disinfect water by eliminating bacteria and viruses. Suspended particles can be removed by other methods, such as coagulation-flocculation. Advanced oxidation processes (AOP) continue to be the most common chemical treatment methods. These are based on the formation of a highly reactive radical, the hydroxyl radical ($\cdot\text{OH}$), which has a very short lifetime, a high oxidation potential and a high reactivity towards many organic compounds (Mansour et al., 2011).

2.1.3 Biological treatment

Biological treatment of contaminated water is an important approach to sustainable water management, using biological processes to reduce organic, inorganic and microbiological pollutants. These techniques use the ability of micro-organisms, such as bacteria, algae and fungi, to break down or transform contaminants into less harmful compounds. This method uses micro-organisms to break down organic pollutants in the water. This type of treatment is frequently used by wastewater treatment plants in their secondary processes to treat wastewater before it is discharged or reused. Biological treatment of contaminated water is a method used to break down pollutants in water using micro-organisms. These micro-organisms, such as bacteria and fungi, disintegrate harmful organic substances and transform them into non-toxic compounds. Pollutants such as biodegradable

organics, synthetic organic compounds, ammonia, nitrates, iron and manganese can be removed by biological processes (**Ahmed et al., 2017**).

There are several techniques for the biological treatment of contaminated water, including:

1. Activated sludge treatment: This method involves the use of aerobic bacteria to break down organic substances in the water. The micro-organisms are grown in a tank where they metabolise the pollutants, leaving the water purified.

2. Biological filters: In this method, contaminated water is passed through a filter medium filled with bacteria or fungi. These micro-organisms break down the contaminants in the water. Biological filters are often used in wastewater treatment systems.

3. Artificial marshes: Artificial marshes are systems built to mimic natural water purification processes. The plants and micro-organisms in the marsh soil help to break down contaminants and purify the water passing through them.

4. Biofilms: Biofilms are communities of micro-organisms that develop and adhere to solid surfaces, such as plastic supports or pipes. These biofilms can be used to break down pollutants in the water by using them as a support for the growth of micro-organisms. The potential development of microbial strains resistant to treatment processes is another major concern that could compromise the effectiveness of biological treatment. To ensure their effectiveness against a wider range of contaminants, biological treatment systems need to be more robust and adaptable (**Johnson et al., 2022**).

These challenges highlight the need for ongoing research to optimise these technologies and develop adaptive strategies capable of managing the complexity of real wastewater (**Johnson and al., 2023**).

Biological treatment techniques offer a promising solution to the persistent problem of water contamination. Continuous innovation in this field is essential to improve treatment efficiency, reduce operating costs and minimise environmental impact. Furthermore, to meet future water quality and water security challenges, a holistic approach integrating these technologies within sustainable water management strategies is essential (**Ahmed et al., 2017**).

2.1.4 Electrocoagulation

A promising method for treating contaminated water is electrocoagulation, which uses electric current to remove impurities. This process involves using an electric current to destabilise and aggregate contaminants, separating them from the water. Heavy metals, organic compounds and suspended solids, industrial wastewater, municipal water supplies and other contaminated water sources are just some of the pollutants that have attracted the method's attention. Recent studies have shown that electrocoagulation can be an effective and sustainable solution for water treatment. For example, a study by **Gao et al. (2020)** demonstrated that electrocoagulation was effective in removing heavy metals from industrial wastewater, highlighting its effectiveness in solving water pollution problems. In addition, **Zhang et al. (2019)** demonstrated the use of electrocoagulation in the treatment of organic pollutants, highlighting its ability to solve a variety of contamination problems. According to **Mollah et al. (2021)**, electrocoagulation has proved to be a promising technique for treating contaminated water, offering significant advantages in terms of treatment efficiency and environmental sustainability. Thanks to its ability to effectively reduce the pollutant load while minimising sludge production, this technology presents a viable alternative to traditional water treatment methods, the authors point out. Research has shown that this technology presents a viable alternative to traditional water treatment methods, thanks to its ability to effectively reduce the pollutant load while minimising sludge production. According to **Hakizimana et al. (2017)**, over the past ten years, numerous reviews have been conducted on the electrocoagulation (EC) process, which remains a very active area of research. Most published research focuses on methods for treating drinking water and urban, industrial or agricultural wastewater in order to simultaneously improve the reduction of soluble and colloidal pollution. Due to the lack of systematic models for scaling up reactors, despite the many advantages and disadvantages of CE reported in the literature, its industrial application is not yet considered an established wastewater treatment technology. In addition, it helps to understand the theory, electrode materials, operating conditions, reactor design and even techno-economic analysis. The parameters affecting EC efficiency are related to operating conditions such as current or voltage and operating time, water and wastewater characteristics such as pH, alkalinity and conductivity, and the geometry of the EC reactor and EC electrodes (electrode surface, electrode spacing).

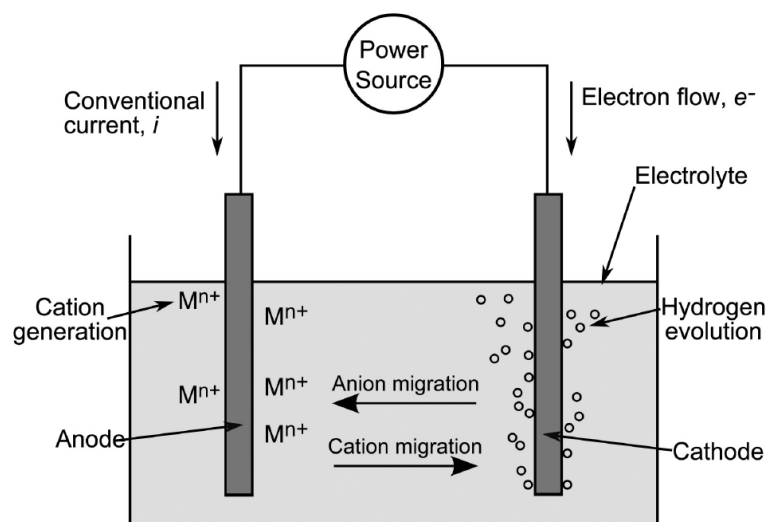


Figure 1: Schematic of an electrocoagulation (EC) cell.

2.1.5 Nanotechnology

Nanotechnology appears to be a promising area for solving water contamination problems. Because of its potential to provide efficient and cost-effective solutions, the use of nanotechnology in the treatment of contaminated water has attracted particular attention. According to **Wang et al. (2021)**, nanotechnology offers innovative approaches to the treatment of contaminated water, underlining its importance in solving environmental problems. However, despite the potential benefits of using nanotechnology in water treatment, there are a number of issues to be resolved. The potential environmental impact of nanomaterials used in water treatment processes is one of the key issues. As pointed out by **Zhang et al. (2020)**, the release of nanomaterials into the environment can raise concerns about their long-term effects on ecosystems and human health. In addition, there are concerns about the scalability and practical implementation of nanotechnology-based water treatment systems. As discussed by **Sharma et al. (2019)**, the application of nanotechnology at the laboratory scale to real-world water treatment facilities presents technical and economic challenges. The combination of these factors highlights the importance of comprehensive research and development efforts to solve the problems associated with nanotechnology-based water treatment. The researchers aim to develop advanced water treatment technologies capable of effectively removing contaminants from water sources by taking advantage of the unique properties of nanomaterials, such as their large surface area and reactivity.

Nanotechnology-based treatment of water and wastewater promises not only to overcome the major challenges facing existing treatment technologies, but also to provide new treatment capabilities that could enable cost-effective use of unconventional water sources to increase water supply (**Qu et al., 2013**).

2.2 Methods for cleaning up contaminated soil

The remediation of contaminated soil is a major environmental issue that is attracting the attention of political decision-makers and the scientific community worldwide. Industrial activities, intensive agriculture, accidental chemical spills and inadequate waste management are just some of the many sources of soil contamination. The rehabilitation of contaminated soils is the objective of remediation techniques to protect human health, preserve ecosystems and enable sustainable land use. Consequently, contaminated soil purification techniques are crucial to the management of polluted sites.

The complexity of contaminated soils requires the creation of strategies tailored to each situation to ensure effective remediation while minimising environmental effects (**Brown et al., 2019**). Therefore, in order to address this complex issue, it is essential to explore the different remediation methods available. The remediation of contaminated soils requires a personalised and multidisciplinary approach due to the variety of contaminants and geological and climatic contexts (**Johnson & Anderson, 2022**). This observation highlights the need for in-depth assessment of contaminated sites and customised remediation strategies.

There are a number of remediation methods that can be classified according to how they are used.

- 1- Off-site treatment (ex situ) consists of excavating or extracting the polluted medium (waste, soil, water) and evacuating it to a suitable treatment centre;
- 2- On-site treatment involves excavating and then treating the polluted medium on site;
- 3- In situ treatment consists of degrading, fixing or extracting the pollutant from the environment without excavation;
- 4- Containment (in situ) involves preventing or limiting the migration of pollutants.

Remediation methods can be divided into three main categories: physical, chemical and biological.

1. Physical methods: These methods involve the extraction or isolation of contaminants. The most common example is the excavation of contaminated soil followed by its treatment or safe disposal. Another physical method is containment, which aims to prevent the spread of contaminants through the use of physical barriers. Physical methods such as solvent extraction and in situ stabilisation have shown promising results in cleaning up soil contaminated by polycyclic aromatic hydrocarbons (PAHs) by significantly reducing their concentration in the soil (**Smith et al., 2021**).

2. Chemical methods: These techniques use chemical reactions to neutralise or extract contaminants from the soil. Stabilisation/solidification is a common chemical method that involves adding binders to the soil to immobilise contaminants. Thermal desorption, which heats the soil to vaporise volatile contaminants, is another chemical method used. The use of chemical decontamination techniques raises a number of important issues. Firstly, the effectiveness of these methods can vary considerably depending on the type of contaminant and the characteristics of the soil. Secondly, there is growing concern about the potential side-effects of certain chemical treatments on the non-target environment, including flora and fauna. Finally, it is important to consider the cost and technical feasibility of these interventions (**Johnson et al., 2023**).

3. Biological methods:

Also known as bioremediation, these methods use micro-organisms or plants to degrade or absorb contaminants. Phytoremediation uses certain plants capable of absorbing or stabilising contaminants in their tissues.

Microbial bioremediation uses specific bacteria or fungi to break down organic pollutants. Soil decontamination is a major challenge for the environment and public health. Biological methods offer a promising alternative to traditional techniques, which are often costly and sometimes not very environmentally friendly. Biological techniques for remediating contaminated soil use micro-organisms and plants to degrade, transform or immobilise contaminants (**Chekol et al., 2002**).

2.3 Remediation of contaminated water and soil by phytoremediation

Phytoremediation involves using plants to eliminate pollution from soil, water or air. The term comes from the Greek phyto, meaning plant, and the Latin remedium, meaning to restore balance

(**Bensari, 2021**). It is a method that uses plants to reduce, extract or degrade environmental pollutants. This is a method of decontaminating contaminated water and soil. It is seen as a cost-effective and environmentally friendly alternative to traditional clean-up methods. Phytoremediation offers a potentially cheaper and more aesthetically pleasing solution to soil and water contamination, compared with traditional clean-up methods, say (**Newman, 2004**). Phytoremediation offers considerable advantages in terms of cost, effectiveness and environmental compatibility. It is effective and affordable, enabling contaminated sites to be renovated while preserving soil quality (fertility). There are several ways in which plant species can destroy pollution. Phytoremediation techniques include phytoextraction (or phytoaccumulation), phytofiltration, phytostabilisation, phytovolatilisation and phytodegradation (**Ali et al., 2013**). In contrast to its many positive aspects, phytoremediation has some drawbacks and limitations, which are:

- 1- It is limited to the rooting depth of the remedial plants;
- 2- Remediation by plants is a lengthy process, so cleaning up hazardous waste can take several years or more;
- 3- Using non-native invasive species can affect biodiversity;
- 4- Consumption of contaminated plants by wildlife is also a cause for concern;
- 5- An unfavorable climate is another important consideration, as it can limit plant growth and phytomass production, thereby reducing the efficiency of the process.

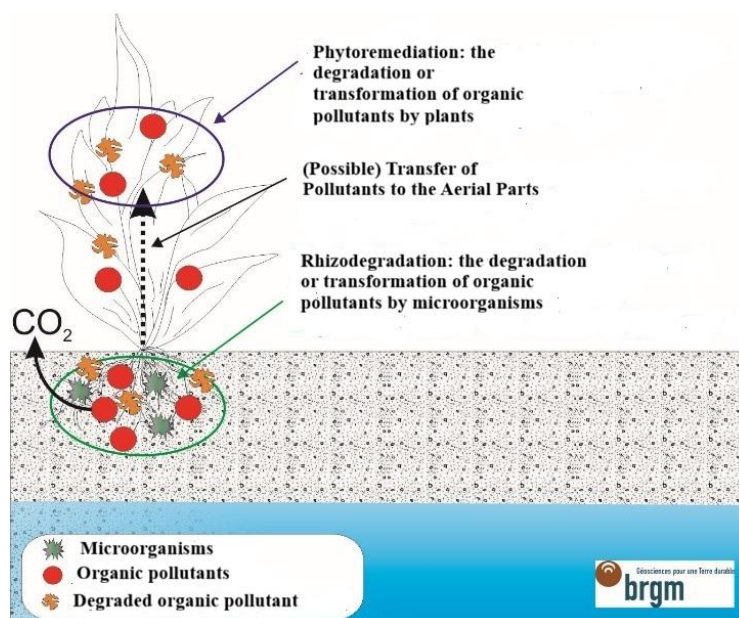


Figure 2: Phytoremediation diagram

2.4 Remediation of contaminated water by phytoremediation

Water pollution is a global problem that affects human health and aquatic ecosystems. Industrial, agricultural, domestic and urban discharges are just some of the many sources of this pollution. Faced with this threat, it is essential to find effective and sustainable solutions. Because of its ability to treat a variety of contaminants, including heavy metals, volatile organic compounds and excessive nutrients, phytoremediation is emerging as a promising alternative.

Cleaning up contaminated water is a major challenge for public health and the environment. Phytoremediation differs from other existing methods in its ecological and sustainable approach. In this method, plants are used to absorb, degrade or immobilise pollutants present in water, soil or air (Origo et al., 2024). This process depends on the plants' ability to absorb and accumulate contaminants from the soil and water. Phytoremediation has become a popular method of treating contaminated water because of its effectiveness, low cost and reduced environmental impact compared with traditional clean-up methods. According to Zhang et al. (2020), the importance of phytoremediation in the current context of cleaning up contaminated water is that it emphasises that phytoremediation offers a sustainable and environmentally friendly approach to restoring water quality by eliminating various pollutants. The selection of appropriate plants for each type of pollutant and the optimisation of environmental conditions to promote the effectiveness of the process are the problems associated with the depollution of contaminated water by phytoremediation. Choosing the right plants for each type of pollutant is crucial to the success of phytoremediation. The most effective plant-based method for removing pollutants from contaminated areas is phytoremediation of metals. Green technology can be used to clean up polluted soil without damaging the soil structure. It has been shown that particular plants, such as grasses and woody species, have a remarkable capacity to absorb toxic metals (Muthusaravanan et al., 2018).

2.5 Phytoremediation mechanisms

Phytoremediation is a recently developed field of science and technology that uses plants to clean up polluted soil, groundwater and wastewater. The use of green plants, including grasses and woody species, to remove, contain or render harmless environmental contaminants such as heavy metals, metalloids, trace elements, organic compounds and radioactive compounds present in soil or water is known as phytoremediation. All plant-influenced biological, chemical and physical processes that contribute to the uptake, sequestration, degradation and metabolism of contaminants, either by plants, soil microbes or plant-microbial interactions, are included in this definition.

According to Muthusaravanan et al. (2018), phytoremediation of heavy metals from contaminated sites generally occurs through one or more of the following mechanisms or processes:

- 1- Phytoaccumulation;
- 2- Phytostabilisation ;
- 3- Phytodegradation ;
- 4- Phytovolatilisation;

5- Rhizofiltration.

Different phytoremediation processes for HM uptake (Bian et al., 2018).

Table: Various phytoremediation processes

Types of phytoremediation	Scope of application	Mechanism	Contaminant
Phytovolatilisation	Volatile contaminants	Volatilisation by leaves	Organic/Inorganic
Phytostabilisation	Mining contamination	Complexation	Inorganic
Phytoextraction	Weakly or moderately contaminated sites	Hyper accumulation	Inorganic
Rhizofiltration	Waste water	Rhizosphere accumulation	Organic/Inorganic

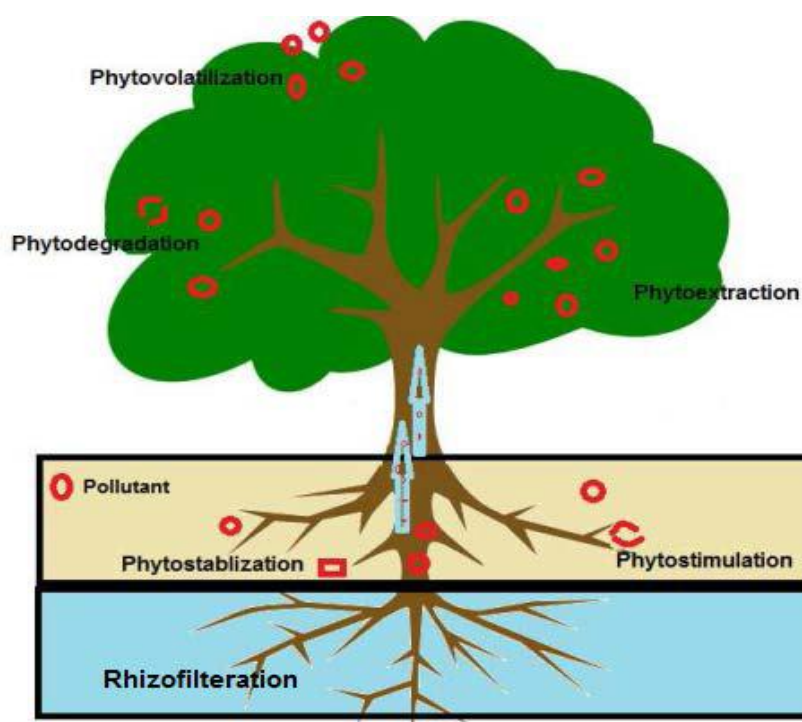


Figure 3: Phytoremediation process

2.5.1 Phytoextraction

This method uses the ability of plants to absorb toxic substances through their roots, concentrate them in their aerial parts and then harvest them to eliminate the contaminants. Phytoextraction is considered to be an environmentally friendly method of restoring contaminated soils because it avoids the excavation and transportation of polluted soils to disposal sites (Nedjimi, 2021)

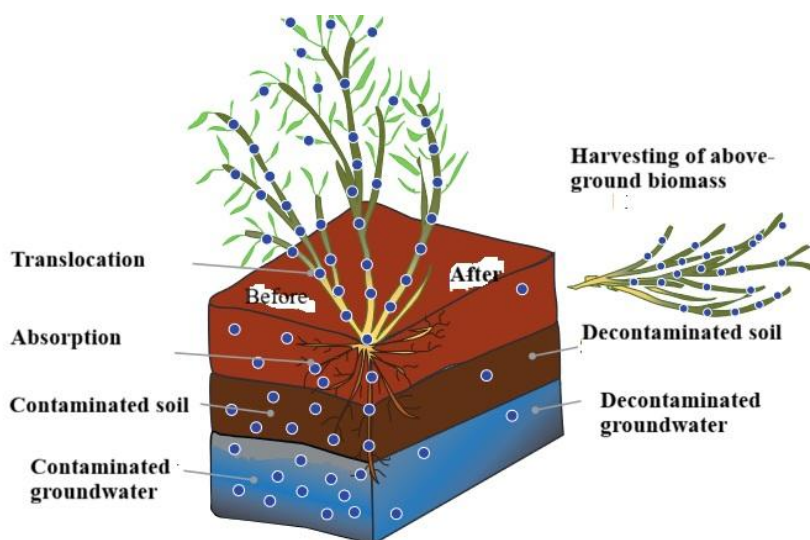


Figure 4: Phytoextraction process

2.5.2 Rhizofiltration

Rhizofiltration is a phytoremediation technique that uses plant root systems to eliminate contaminants from soil or water.

It is a technique for eliminating water pollutants and liquid waste by precipitating toxins on the surface roots or absorbing soluble pollutants in the roots (Nedjimi, 2021; Ali et al., 2020).

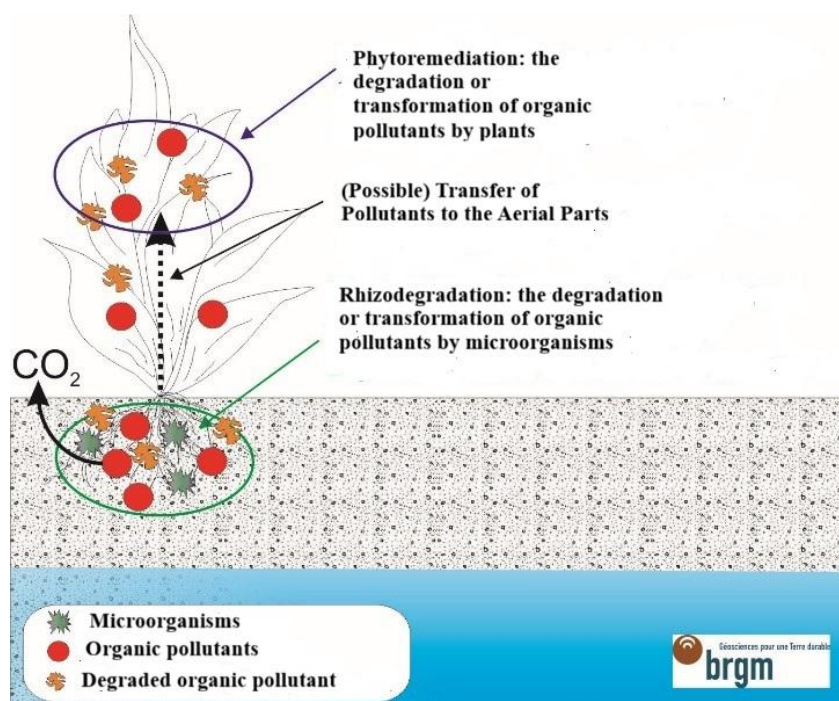


Figure 5: Rhizofiltration process

2.5.3 Phytovolatilisation

This can be defined as a process of absorption and transformation of pollutants into less harmful volatile forms. The pollutants are assimilated by the roots, transferred to the shoot and volatilised into the atmosphere through the stomatal leaves (Nedjimi, 2021; Abdel-Shafy & Mansour, 2024). Phytovolatilisation can occur with contaminants present in the soil, sediments or water. Mercury is the main metallic contaminant for which this process has been used.

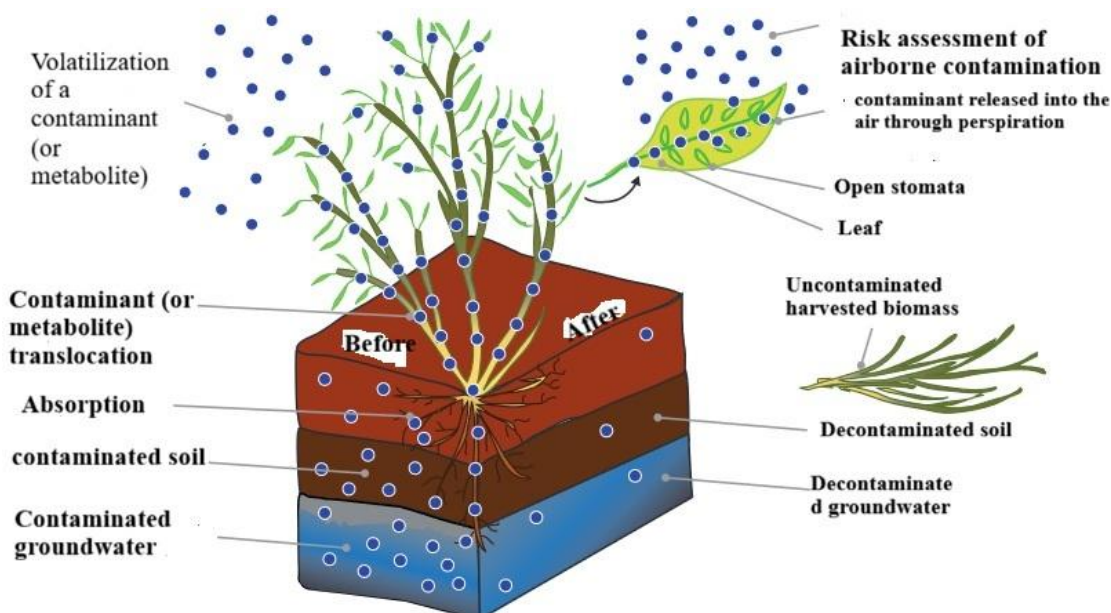


Figure 6: Phytovolatilisation process

2.5.3 Phytostabilisation

Phytostabilisation is a method of managing contaminated sites that uses plants to immobilise and stabilise pollutants in the soil and prevent them from spreading into the surrounding environment. This method is particularly effective in combating soil contamination by heavy metals and other types of pollution.

Phytostabilisation has many advantages, including its ability to restore biodiversity and improve overall soil quality, as well as its low intrusiveness compared with other soil remediation techniques (Hénault, 2016; Abdel-Shafy & Mansour, 2024).

2.5.3 Phytodegradation

Phytodegradation or phytotransformation is the degradation of pollutants assimilated by plants through a metabolic process, or the degradation of pollutants outside the plant by enzymes produced by the roots (such as dehalogenases, nitroreductases and peroxidases) and can be considered as a natural process that involves the use of plants to degrade, break down or eliminate pollutants present in the soil, water or air.

Phytodegradation is widely studied because of its potential to be used as an environmentally friendly pollution treatment method (Nedjimi, 2021).

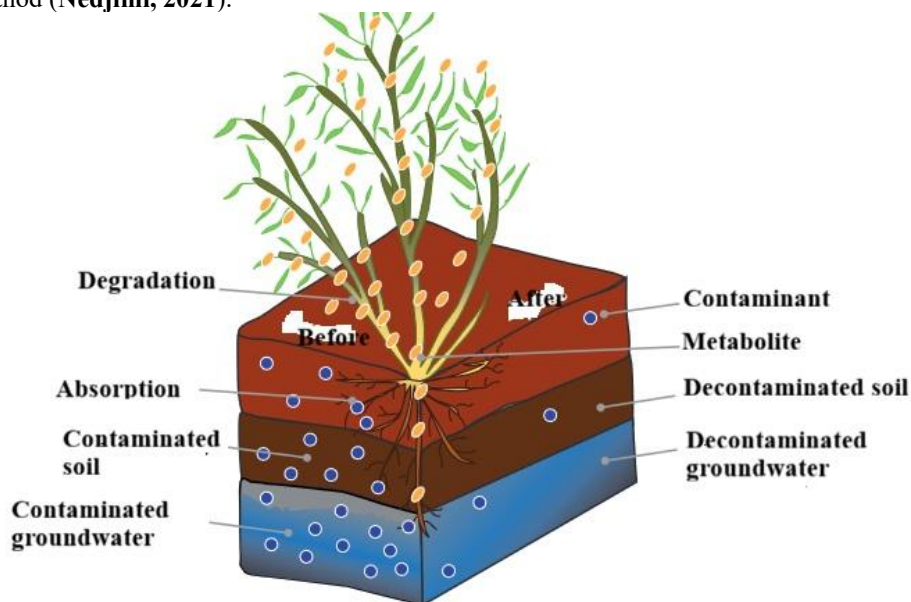


Figure 7: Phytodegradation process

III. CONCLUSION

The purification of contaminated water and soil using remediation methods is promising and ecologically sustainable. They offer a number of advantages, including lower costs than traditional remediation methods, reduced environmental disturbance and the ability to target a variety of contaminants, such as pesticides, heavy metals and certain volatile organic compounds.

However, depending on the type of contaminant, its concentration, the type of soil or water and the plant species used, its effectiveness can vary. What's more, phytoremediation takes longer than conventional methods. In short, although phytoremediation is highly effective in eliminating pollution from contaminated water and soil, it must be used with care every time. Future research should focus on improving the effectiveness of all these methods and exploring best practice for their use in different environmental contexts.

The study concludes that phytoremediation is a promising alternative for restoring soil and water quality while protecting human health and biodiversity.

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CONFLICTS OF INTEREST

This article does not involve any conflicts of interest, and the authors support the publication of their work in this journal.

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