CHAPTER

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The trend of bioremediation as an effective technology in soil decontamination

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Ubiratan Alegransi Bones
Master, Federal University of Santa Maria
E-mail: ubiratan.bones@acad.ufsm.br

Kauane Andressa Flach
Master, Federal University of Santa Maria

Genesio Mario da Rosa
Doctor, Federal University of Santa Maria

ABSTRACT

This paper reviews the different techniques of bioremediation as a technology that uses living organisms, such as bacteria, fungi, and plants, to remove, degrade or transform contaminants present in soil, water, or air into less harmful substances. The research highlights the advantages of bioremediation for the mitigation of anthropogenic impacts on the environment, especially those caused by the use of herbicides and insecticides in agricultural practices. In addition, bioremediation can degrade a wide variety of contaminants, including hydrocarbons, heavy metals, pesticides, and toxic organic compounds, which can accumulate in the medium or be leached to contaminate water sources. In this context, it is emphasized that bioremediation can be applied directly to the contaminated site, reducing the need for the removal and transportation of large amounts of contaminated soil. This results in lower environmental impact and lower cost compared to other decontamination techniques. Another advantage of bioremediation is the integration of degraded contaminants into biogeochemical cycles, which contributes to the recovery of soil fertility and water quality. The technique also preserves biodiversity and ecosystem services, which can be affected by other decontamination techniques that alter the physical and chemical characteristics of the environment. However, there are also challenges and limitations of bioremediation, such as the possibility of partial degradation of the target compound and the formation of a more toxic or persistent by-product. This can occur due to the dependence on favorable environmental conditions, such as nutrients, oxygen, pH, composition, concentration, and bioavailability of contaminants, as well as the physical and chemical characteristics of soil and water. In addition, bioremediation is a promising tool for promoting the health and quality of life of populations affected by environmental contamination, but it requires an in-depth knowledge of the processes involved and a careful assessment of the risks and benefits.

Keywords: Environment, anthropic impacts, decontamination.

1 INTRODUCTION

The concern generated by anthropogenic impacts on soil and water has been necessary for mitigatory measures to be taken.

One of the main motivators of the studies has been the contamination caused by the use of herbicides and insecticides in agricultural practices, which can accumulate in the environment or be leached to contaminate water sources.

Due to these impacts, some technologies have been adopted, especially bioremediation, which uses living organisms, such as bacteria, fungi, and plants, to remove, degrade or transform toxic substances or contaminants present in soil, water or air into less harmful substances, which are integrated into biogeochemical cycles (FASANELA and CARDOSO, 2016).

One of the main advantages of bioremediation is its ability to degrade a wide variety of contaminants, including hydrocarbons, heavy metals, pesticides, and toxic organic compounds.

The microorganisms present in the soil can use these substances as a source of energy and nutrients, transforming them into harmless or less toxic compounds.

In addition, some microorganisms can even metabolize highly persistent substances, such as petroleum hydrocarbons (ANDRADE et al., 2010; ATLAS & HAZEN, 2011).

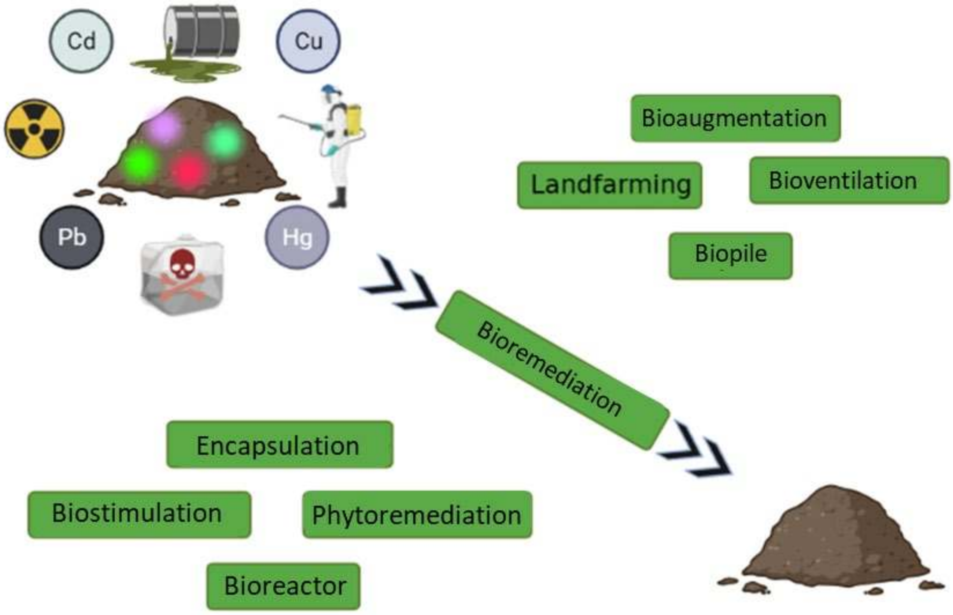
Another positive point of bioremediation is its direct application at the contaminated site, which reduces the need to remove and transport large amounts of contaminated soil.

This results in lower environmental impact and lower cost compared to other decontamination techniques (TAVARES, 2018).

However, it is important to emphasize that the bioremediation procedure can also bring harm to the system, such as partial degradation of the target compound and the formation of a more toxic by-product.

In addition, this process is often slow and requires favorable conditions of nutrients, oxygen, pH, composition, concentration and bioavailability of contaminants, as well as the physical and chemical characteristics of the contaminated environment.

According to Tortora, et al. (2005), some synthetic chemicals are composed of bonds and subunits subject to attack by bacterial enzymes. Small differences in chemical structure can modify the efficiency of biodegradability.



2 CONTAMINATION PROBLEM

Soil pollution is a global problem that has its origins in anthropological and natural sources. Urbanization, industrialization and increased demand for natural resources have required the use of compounds, substances and chemical agents that, over the years, have caused the dispersion and accumulation of pollutants in the environment (RAFFA and CHIAMPO, 2021).

Soil contamination can be defined as the accumulation in the soil of persistent harmful substances, chemical compounds, radioactive waste, salts, pathogens and others that harm biological systems (OKRENT, 1999; MAREDDY, SHAH AND DAVERGAVE, 2017).

Thus, the increased levels of toxic compounds in the soil affect the balance of ecosystems and human health (PALANSOORIYA et al., 2020).

When a pollutant reaches the soil, it can be adsorbed, carried away by the wind and the flood, or leached by the infiltration water, passing to the lower layers and reaching the groundwater (CETESB, 2020).

The main sources of soil contamination include residues of agricultural inputs, by-products, air pollutants, irrigation, floods, accidental oil spills, improper management of municipal waste and sewage, heavy metals, deposition of petroleum products and other hydrocarbons (MONTANARELLA et al., 2015).

The improper disposal of these contaminants in the environment is causing serious damage to all forms of life, in part due to increased global industrialization (QUINTELLA, MATA and LIMA, 2019).

Pollutants such as petroleum hydrocarbons, heavy metals and pesticides are harmful to the health of ecosystems. In humans, there may be incidence of carcinogenesis and mutagenesis, as well as other toxic effects (KUPPUSAMY et al., 2020).

Heavy metals, for example, can accumulate in living tissues and be transferred to higher trophic levels, a phenomenon known as bioaccumulation (OLIVEIRA et al., 2007).

The remediation of contaminated sites is essential to recover their ecological functions, aiming at environmental preservation and social development.

The methods available for soil remediation can be grouped into three categories, namely: chemical, physical and biological methods, the latter being amenable to insertion in the polluted site *(in situ)* or outside it (*ex situ)* (SALES DA SILVA et al., 2020).

3 MICROBIOLOGY AS THE MAIN ALLY IN SOIL BIOREMEDIATION

There are billions of microorganisms present in the soil. Such a vast population ends up forming a great ecosystem due to the variety of molecules and nutrients possible to be found in the soil. From the simplest organic matter or pollutants carried to certain places, they will be incorporated into the soil as a form of energy transformation, following the natural flow of terrestrial life.

Second Tortora (2005), we can think of the soil as if it were a "biological fire". A leaf that falls from a tree will be consumed and metabolized by soil microbes.

The elements of this leaf enter the biogeochemical cycles, where the elements undergo oxidation and reduction by the action of these microbes to cure their metabolic needs or assist plants in the absorption of nutrients (MIRANSARI, 2013). Among these cycles, we can mention: carbon, phosphorus, nitrogen and sulfur.

The organisms present in the soil can be from prokaryotic such as bacteria and archaea (which comprise two of the three domains of life); even eukaryotic organisms, where fungi stand out. Also present are insects, nematodes, protozoa, algae, oligochaetes (earthworms); and even viruses, which still have their role little explored in this environment (BRADY; WEIL, 2013).

In this sense, table 1 presents the main compounds that represent problems soil contamination and which microorganisms are generally used for its recovery.

Table 1 – Soil contaminants and bioremediating microorganisms

Compounds	Microorganisms
Hydrocarbon	Penicillium chrysogenum, P. alcaligenes P. mendocina, P. veronii, Achromobacter, Flavobacterium, Acinetobacter, Pseudomonas putida, Phanerochaete chrysosporium, A. niger, A. fumigatus, F. solani e P. funiculosum, Coprinellus radians, Alkaligenes odorans, Bacillus subtilis, Corynebacterium propincum, Pseudomonas aeruginosa, Tyromyces palustris, Gloeophyllum trabeum, Trametes versicolor, Candida viswanathii, cianobactérias, algas verdes e diatomáceas e Bacillus licheniformis, Ralstonia sp. e Microbacterium sp,, Gleophyllum striatum, Pseudomonas sp.
Petroleum	Fusarium sp., Alkaligenes odorans, Bacillus subtilis, Corynebacterium propincum, Bacillus cereus A, Aspergillus niger, Candida glabrata, Candida krusei e Saccharomyces cerevisiae, B. brevis, P. aeruginosa KH6, B. licheniformis e B. sphaericus, P. putida, Arthobacter sp e Bacillus sp, Pseudomonas cepacia, Bacillus coagulans, Citrobacter koseri e Serratia ficaria
Dyes	B. subtilis estirpe NAP1, NAP2, NAP4, Myrothecium roridum IM 6482, Pycnoporus sanguinous, Phanerochaete chrysosporium e trametes trogii, Penicillium ochrochloron, Micrococcus luteus, Listeria denitrificans e Nocardia atlântica, Bacillus spp. ETL-2012, Pseudomonas aeruginosa, Bacillus pumilus HKG212, Exiguobacterium indicum, Exiguobacterium aurantiacums, Bacillus cereus e Acinetobacter baumanii, Bacillus firmus, Bacillus macerans, Staphylococcus aureus e Klebsiella oxytoca
Heavy metals	Saccharomyces cerevisiae, Cunninghamella elegans, Pseudomonas fluorescens e Pseudomonas aeruginosa, Lysinibacillus sphaericus CBAM5, Microbacterium profundus cepa Shh49T, Aspergillus versicolor, A. fumigatus, Paecilomyces sp., Terichoderma sp., Microsporum sp., Cladosporium sp., Geobacter spp., Bacillus safensis (JX126862) cepa (PB-5 e RSA-4), Aeromonas sp., Aerococcus sp., Rhodopseudomonas palustris
Pesticide	Bacillus, Staphylococcus, Enterobacter, Pseudomonas putida, Acinetobacter sp., Arthrobacter sp., Acenetobactor sp., Pseudomonas sp., Enterobacter sp. e Photobacterium sp.

References: (PENG, 2018; ZENG et al., 2020; LIU et al., 2022; ATUCHIN et al., 2023; SINGH, TRIPATHI E CHANDRA, 2023)

The different groups of organisms present in the soil are commonly studied separately giving rise to didactic separations of them, such as the division into the so-called soil fauna: macrofauna (larger organisms), mesofauna (of intermediate size) and soil microfauna (smaller organisms) (GILLER, 1996).

About smaller organisms, the functions are more numerous, mainly due to the greater metabolic diversity found in bacteria, fungi and archaea when compared to other organisms that are components of soil biology.

This greater diversity is directly related to the genetic and metabolic variability present in such organisms, which is due to their origin and evolution, making them the main component of the metabolism of the soil system.

This essentiality is the result of the functions performed exclusively by microorganisms, and by their numerical dominance over the others (GILLER, 1996).

According to Fasanela and Cardoso (2016), considering the existence of different types of soil existing throughout the planet, it is noticeable that in some cases, different types of microorganisms perform the same functions in different locations.

The opposite also occurs, and even in different places the same types of microorganisms can be found performing different functions.

This happens due to the difference in factors such as: ph, temperature, pressure, soil composition. Environmental conditions can cause various reactions in organisms, directing their adaptation abilities.

Microbial abundance and diversity are actively involved in plant development, catabolizing organic matter, and acting on nutrient mineralization, nitrogen fixation, pest protection and pathogen control (ZAK et al., 2003).

3.1 SOIL CONTAMINATING COMPOUNDS

As described by Fasanela and Cardoso (2016), soil contaminants can be classified in several ways (Table 2), and one of these divisions gives rise to three groups:

Table 2 – Soil contaminants are classified into three groups

CONTAMINANT	DESCRIPTION
Biodegradable compounds:	In most environmental conditions, they are biodegradable and usually have molecules similar to those naturally present in the soil, such as components of organic matter.
Persistent compounds:	Biodegradability depends on specific conditions, for example, only in the presence of O2, when oxidative metabolic processes can promote the breakdown of certain components.
Recalcitrant compounds:	Molecules that have a low level of decomposition due to the enzymatic activity of soil organisms. The cause of recalcitrance may be related to the characteristics of the pollutant, such as low solubility, high molecular adsorption to soil

	components, high toxicity of the compound, or the generation of intermediate compounds toxic to soil organisms.

4 DIFFERENT METHODS AND MANAGEMENT OF BIOREMEDIATION

4.1 BIOSTIMULATION

It is a usual technique that aims to increase the microbial activity of the native soil population by adding nutrients such as nitrogen (N) and phosphorus (P) and/or introducing surfactants, increasing the bioavailability of the contaminant (GAYLARDE et al., 2005).

The stimulation can be done to obtain better removals of pollutants, modifying some factors, such as: improving the aeration of the soil, monitoring and correcting its humidity, its pH and adding nutrients (BAPTISTA, CAMMAROTA AND FREIRE, 2001).

Biostimulation is a technique that improves microbial remediation by providing additional inorganic nutrients, aeration, and moisture, and maintaining proper pH and temperature in contaminated soil.

In cold climate regions, bioremediation can be negatively affected due to low nutrient levels, low availability of contaminants and environmental factors such as pH, temperature and humidity (COUTO et al., 2014).

Studies have shown positive effects of different biostimulation strategies to overcome these limitations (SI-ZHONG et al., 2009).

In addition, the application of surfactants can increase the bioavailability of contaminants to be further metabolized. Addition of substrates such as petroleum sludge and derivatives, wastewater, and sunflower oil contributes to co-metabolism (TOMEI AND DAUGULIS, 2013).

Easily degradable substrates act as a primary source of nutrients, as a source of energy, by favoring microbial growth. Consequently, microorganisms further degrade hydrocarbon contaminants using them as secondary substrates.

An innovative bioremediation technique has been developed using spray foam, which is capable of raising the soil temperature.

This approach involves the release of nutrients, surfactants and microbial agents through the foam, which is applied to the top layer of the soil, acting as a thermal insulator (JEONG et al., 2015).

In addition, the use of heating facilities, biobatteries, composting and bioreactor technologies such as landfarming can also be employed to maintain a temperature favorable to the bioremediation process.

4.2 BIOREACTOR

In the Bioreactor system, the excavated contaminated soil is transformed into sludge when it is mixed with water. This material is placed in the bioreactor with continuous agitation.

The system can be operated in different feeding modes, such as batch, semi-continuous and continuous. Several physical and biological parameters, such as temperature, pH, aeration, agitation, bacterial inoculum, nutrients and substrate, can be controlled in the bioreactor (TOMEI, DAUGULIS, 2013).

Sludge bioreactors have been used to remediate total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAH) and other soil contaminants.

With this methodology, pollutant removal rates of 60 to 100% were achieved (JOHNSEN et al., 2005; CHIKERE et al., 2016).

Due to its functional characteristics, this technique has been considered promising for removing pollutants from soils in cold regions.

However, the sludge bioreactor strategy is laborious, time-consuming, and expensive and demands post-remediation treatments (dewatering and wastewater treatment) (CHIKERE et al., 2016; ANGELUCCI and TOMEI, 2016).

4.3 BIOAUGMENTATION

It occurs by inoculation of microorganisms grown biotechnologically, in the contaminated site, without negatively interfering in the biogeochemical performance of the natural microorganisms of that environment.

They can be used to degrade hydrocarbon chains within a contaminated natural system. These microorganisms then start to use the polluting organic compound as a carbon source, thus causing a reduction in its concentration over time (DEON et al., 2012).

However, results published by Ruberto et al., (2010), with allochthonous microorganisms, demonstrate that the technique faces efficiency problems in cold regions.

In contrast to the author's results, when applied in favorable environments, autochthonous organisms have been shown to act effectively in cold soil.

This is because cold environments are generally unfavorable for unnatural microbes, requiring a pre-analysis to discuss the need or not to insert new microorganisms for treatment (STALLWOOD et al., 2005; GRAN-SCHEUCH et al., 2017).

Due to adaptability issues and legal environmental impediments to the insertion of allochthonous microorganisms, the stimulation of natural autochthonous microbes to the cold climate is more appropriate for bioremediation. However, the restrictions can be overcome when bioaugmentation is applied ex-situ, with controlled techniques (AISLABIE et al., 2006).

4.4 "LANDFARMING"

This ex-situ technique consists of the application of contaminants or contaminated tailings on the surface of the uncontaminated soil to stimulate degradation.

The tailings are incorporated into the soil using plowing and grading, in which the soil is dispersed forming a surface of small thickness. However, adjustments in soil conditions are necessary to maximize biological activity (CASTRO et al., 2005).

The treatment in "landfarming" is an efficient way to treat waste and prevent contamination of the environment (HENCKLEIN et al., 2007).

It has been used successfully for decades, such as in the biotreatment of petroleum-derived substances and many are released by the oil refining industries (FASANELA and CARDOSO, 2016).

This method should be monitored periodically so that the reduction of the concentration of the constituents, the emission of vapors, the migration of the constituents in the soil and the groundwater that must be distant from the treatment site can be verified (CARNEIRO and GARIGLIO, 2010).

It is a widely used strategy due to its low cost and easy handling. In addition, it has been applied in a wide range of environmental conditions, including extreme cold and arid soil (TOMEI and DAUGULIS, 2013).

When applied to cold soil, it can be impaired by unstable temperature, freezing and thawing cycles, soil moisture and desiccation (AISLABIE et al., 2004; CAMENZULI and FREIDMAN, 2015).

Aiming at improvement and greater efficiency, this methodology can be incorporated by incorporating bioaugmentation along with the addition of water, fertilizer and surfactants (JEONG et al., 2015).

4.5 PHYTOREMEDIATION

A plant system and its microbiota are used to accelerate the process of soil and water decontamination (PIRES et al., 2003). Plants, specific to each contaminant, can soften or even totally depollute contaminated areas (LEONEL et al., 2010).

However, the efficiency of this technique is obtained using plants that have certain characteristics such as a good absorption capacity, deep root system, accelerated growth rate, easy harvest and that present a great resistance to the pollutant (COUTINHO et al., 2007).

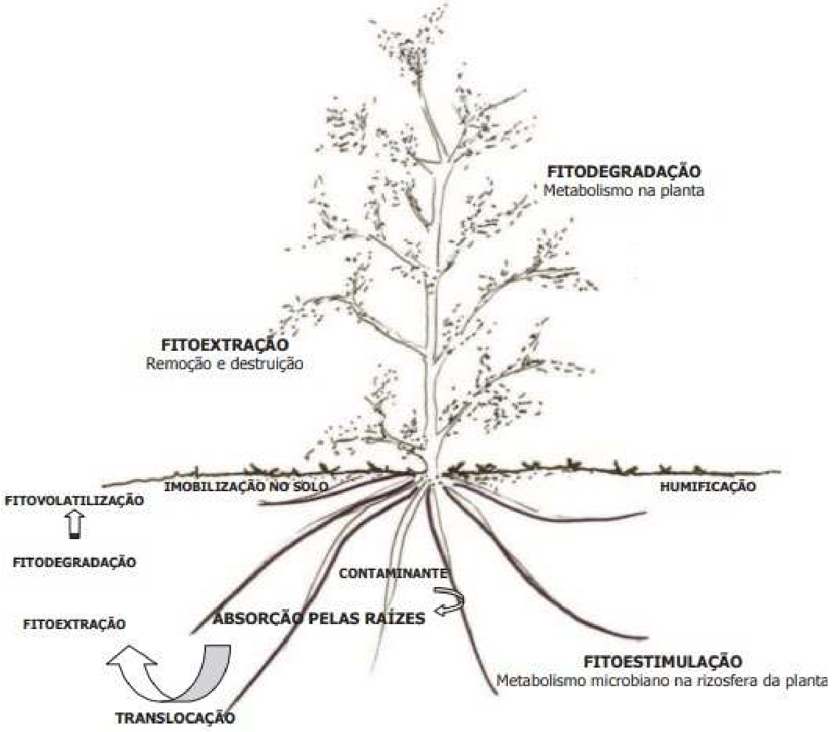
It is advantageous mainly because it has potential for in situ treatment and is economically viable (PIRES et al., 2003). However, the disadvantage of this technique is the dependence on the life cycle of the plant, making it difficult to visualize the results and also the fact that it is possibly part of the food chain, increasing environmental damage (LEONEL et al., 2010).

It also presents the difficulty of use in some types of soils contaminated with a large mixture of chemical compounds, where there is difficulty in selecting a resistant plant for this set of substances (COUTINHO et al., 2007).

Phytoremediation is a multi-technological approach that involves the use of plants for extraction, accumulation, degradation, filtration, stabilization and volatilization of soil and water contaminants. Thus, there are several mechanisms by which plants can perform phytoremediation (Figure 1).

According to Pires et al. (2003), encouraging results were achieved in the area of phytoremediation for heavy metals, petroleum hydrocarbons, pesticides, explosives, chlorinated solvents and toxic by-products of the industry. It is feasible to remove toxic heavy metals through the bioaccumulation process, which resembles the biomining technique (US EPA, 2000).

Figure 1 - Mechanisms used by plants in the phytoremediation process.



Source: ANDRADE et al., (2007)

The various techniques and mechanisms involved in phytoremediation (Table 3). It has its characteristics and efficacy, and the choice of the most appropriate mechanism will depend on the type of contaminant and environmental conditions.

This variety of mechanisms demonstrates the versatility of plants in phytoremediation and highlights their unique ability to interact with the environment in ways beneficial to the removal or reduction of toxic substances.

Table 3 – Main mechanisms of action of plants in phytoremediation

Technique involved	Mechanism of action	Contaminant treated
Phytoextraction	Absorption of contaminants by the roots, where they are stored or transported and accumulated in their aerial parts.	Metals: cadmium, nickel, copper, zinc and lead. Inorganic compounds and organic compounds.
Phytostimulation	Stimulation of microbial activity, promoted by the release of root exudates that act on the degradation of compounds.	Organic compounds. Hydrophobic aromatic chemicals. Herbicides.
Phytotransformation	Plants can absorb contaminants through their roots and transport them to their aerial parts. Thus, they can chemically modify contaminants through metabolic reactions, transforming them into less toxic or less mobile forms.	Organic compounds
Phytostabilization	Plants that help reduce the mobility of contaminants in the soil, promoting their immobilization/encapsulation. Plants can promote this stabilization through their root system, which creates a physical or chemical barrier to the migration of contaminants.	Heavy metals such as lead, cadmium, zinc and arsenic.
Phytovolatilization	Plants that can absorb contaminants through their roots and release them in the form of volatile compounds through their leaves.	Substances Volatile organic chemicals: mercury, selenium and arsenic.
Phytodegradation	Plants that use enzymes produced in their roots to degrade contaminants present in the soil. These enzymes are released by the roots and act in the breakdown of toxic compounds, converting them into less harmful or non-toxic by-products.	Organic contaminants

Source: Adapted from Oliveira et al. (2007).

It is important to emphasize that the efficiency of phytoremediation may vary depending on the type of contaminant, the species of plant used, the environmental conditions and the time required for the process to occur.

Therefore, it is essential to conduct specific studies and evaluations to determine the feasibility and effectiveness of phytoremediation in each case.

To implement a good phytoremediation strategy, site assessment must be made, considering the nature of the contaminants and the appropriate selection of plant species (IKEURA et al., 2016).

Generally, native plants from contaminated regions are promising phytoremediators and their efficiency can be increased by bioaugmentation with rhizobacteria, which alter and degrade nutrients and facilitate the absorption of plant species (ALI et al., 2013).

In the plant-endophyte relationship, plants provide carbohydrates to endophytic bacteria and bacteria help minimize biotic and abiotic stresses that aid plant proliferation, including in extreme cold environments (NISSINEN et al., 2012; MUKHERJEE et al., 2018).

During phytoremediation of hydrocarbon pollutants, they also contribute to decrease the phytotoxicity and evapotranspiration of volatile hydrocarbons (ALI et al., 2012).

4.6 BIOBATTERIES

It consists of building cells or piles of contaminated soil to stimulate aerobic microbial activity within the pile through aeration.

The microbial activity is increased by the addition of moisture and nutrients such as Nitrogen and Phosphorus or organic matter (SILVA, 2004).

In this case, with humidity adjustment of the batteries, usually, a leachate collection system is built (FASANELA and CARDOSO, 2016).

The maintenance of the biocells is simple, with relatively fast treatment and has low cost. The treatment area equipped with facilities for aeration, temperature and humidity control and nutrient corrections favor the proper functioning of the technique.

Because of this, promising results have been reported in the remediation of polluted components, including in cold environments (AISLABIE et al., 2006; CHEMLAL et al., 2012).

With the addition of compost and microbial consortiums, Gomez and Sartaj (2013), found high degradation rates (82%) total petroleum hydrocarbon (TPH) in 94 days with this technique.

In addition, from the biopile, other studies have found degradation rates of the same compound above 70% (GOMEZ AND SARTAJ, 2014; WHELAN et al., 2015).

4.7 BIOVENTILATION

Bioventilation is a bioremediation strategy that uses controlled airflow (gas, oxygen or methane) in the polluted soil of an unsaturated zone to increase the degradation activities of native microbes (ÖSTERREICHER-CUNHA et al., 2004).

This is a technology considered promising, because the availability of molecular oxygen has a great effect on the biodegradation of various compounds (CARNEIRO and GARIGLIO, 2010).

It has easy installation and acquisition, performance in places of difficult access and a small impact on the contaminated area, presenting as limitations the low humidity, presence of high-water table, soils with little permeability and mild temperatures, microbial degradation activity (CARNEIRO and GARIGLIO, 2010).

In addition, nutrients can be added to facilitate microbial growth. The low airflow rate prevents the volatilization of the compounds and ensures microbial degradation (HÖHENER AND PONSIN, 2014; Azubuike et al., 2016).

Bioventilation can also be merged with the soil vapor extraction (EVS) technique, but in this case, it requires a high airflow rate.

This action will be effective in removing volatile compounds through physical processes and non-volatile compounds through biological processes (BRUSSEAU et al., 2013).

Both the individual and merged techniques need to be analyzed before execution, as the need for treatment will vary according to each specific case.

Its efficiency can be increased if combined with other methods, such as air injection. In this case, the injected air removes the water from the pores of the soil, causing desorption of the contaminant from the soil structure, causing it to move to the surface, with the help of the EVS system (TAVARES, 2018).

4.8 ENCAPSULATION

As already discussed in the other methodologies, for field-scale soil treatment, the introduction of microorganisms (bioaugmentation) will not always be the best remediation option due to the long-term impact on the autochthonous microbial community and geochemical composition (SUTTON et al., 2014; CAI et al., 2020).

Thus, an alternative is the immobilization of microorganisms, which allows to protect the environment and inoculated microorganisms (MUTLU et al., 2015; VAN DER HAL, ARIEL AND ANGEL, 2016; RODRIGUEZ-CAMPOS et al., 2018; VARJANI and UPASANI, 2019).

In this sense, the immobilization of microorganisms is a set of techniques, such as adsorption, covalent bonding, entrapment and encapsulation, which consist of binding microorganisms to carrier materials, limiting the microorganisms to the surface or inside a polymer matrix and imitating biofilms in nature.

The immobilization of microorganisms is usually an adjunct during bioremediation (BAYAT, HASSANSHAHIAN AND CAPPELLO, 2015; DZIONEK, WOJCIESZYŃSKA AND GUZIK, 2016).

Immobilization techniques usually increase the degradation yields obtained with free cells or enzymes for a wide variety of pollutants.

According to Park et al. (2021), there was a 39.2% increase in diesel bioremediation yield by encapsulated Pseudomonas aeruginosa. In another study, degradation of Ni (II) by encapsulated *Lysinibacillus* sp improved by 44.5% (SAN KESKIN et al. 2018).

Encapsulation methods can be classified into physical, chemical, and physicochemical by their mechanism of action (Chart 1). However, not all existing encapsulation techniques have been applied for bioremediation or even for cell encapsulation.

Table 1 – Encapsulation methods as a function of the mechanism of action

Physical methods	**Chemical Methods**	**Physico-chemical methods**
Spray drying, fluidized bed, extrusion and freeze-drying	Molecular Inclusion and Interfacial Polymerization	Coacervation, sol-gel process, ionic gelation and liposome formation

Microencapsulation applied in bioremediation has been successful for several genera of bacteria (LAKSHMI et al., 2017; DELNEUVILLE et al., 2019; SAN KESKIN et al., 2018).

Unlike bacteria, although encapsulation works of extracellular enzymes of fungi can be easily found, the complete encapsulation of fungi is scarce for remediation, being used in agriculture, where encapsulation preserves enzymatic activity and increases its potential for biological control (BATISTA et al., 2017; MARUYAMA et al., 2020; Sadañoski et al., 2020).

This may be occurring, as the use of enzymes is not limited by the growth of fungi, nor should it generate public health problems. However, enzymes can be altered by stability and environmental factors, such as temperature or pH (KUCHARZYK et al., 2018).

5 CONCLUSIONS

With the advancement of technologies, there is a growing trend towards more natural solutions. In addition to being widely used, the different techniques of bioremediation, has its efficiency proven by a range of studies.

In this sense, natural attenuation processes can play a significant role in the control of soil contamination plumes.

In addition, these techniques generally demonstrate easy execution, low cost, and greater security to the environment.

Moreover, given the large number of bioremediation techniques discussed in this research, it is possible to treat a wide variety of contaminant products.

These include petroleum, dyes, organic compounds in general, and even pesticides, which represent one of the great problems of today due to their large-scale use.

Nevertheless, there is still a large field of new possibilities to be explored in this area, enabling an even more concrete action which offers simple and low-cost solutions to treat contaminated soils, considering their importance to the maintenance of human life.

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