Chapter

Can Natural Attenuation be Considered as an Effective Solution for Soil Remediation?

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Abstract

Natural attenuation is described as a naturally occurring process, mostly in soils and also in groundwater, without human intervention, which transforms, reduces and destroys the organic and inorganic contaminants. As an eco-friendly, cost-effective and relatively simple technology, natural attenuation is widely used for the treatment of contaminated soils. However, the application of this technology must be carefully controlled and monitored not only for its efficiency and durability over time, but also for the migration of contaminants to ensure no risk to human health and ecosystems. Furthermore, the success of this technique requires a good knowledge of the type of contaminants, the physical and chemical characteristics of the soils, as well as the living actors, including plants, fauna, microorganisms and their interactions, that live in the soils to be treated and that will be involved in this process. The purpose of this chapter is to provide the most recent information regarding the principle of this technology, the role of the living actors and the interactions between plant, fauna and microorganisms, the advantages and disadvantages, and finally to discuss the efficiency of this technique in comparison with other techniques such as phytoremediation or bioremediation. In fine, we will discuss its social acceptability.

Keywords: natural attenuation, soil remediation, social acceptation, organic and inorganic pollutants, plant-fauna-microorganisms interaction

1. Introduction

Several hundred thousand industrial and agricultural sites are polluted in the world today due to an increase in the production, extraction, use, and disposal of chemicals since the industrial and green revolutions. All these anthropic activities, along with natural sources of contaminants, release potentially toxic elements and compounds into the environment that have different behaviors depending on soil properties and their interactions with the ecosystem. The main reasons that contaminants are found in the critical zone are numerous: (i) extraction of minerals and raw materials; (ii) use of agrochemicals, untreated organic wastes as sources of fertilizers and irrigating with wastewater; (iii) insufficient management of urban and industrial and hazardous waste; (iv) combustion of raw materials for energy production; and (v) development of widespread transport networks and infrastructures [1]. As a consequence, it is important to know that nearly half of the soils in the world are degraded [2]. The remediation of these sites becomes then almost impossible in spite of the more or less advanced referencing of the administrations throughout the world. Thus, several billion square meters of polluted land were left abandoned without human intervention. Over time, in these soils, a natural phenomenon of soil remediation, called natural attenuation, will be developed in which all live microorganisms that interact closely with the environmental parameters play an important role in this. Today, natural attenuation shows its good capacity to remediate polluted soils. However, numerous questions arise when applying this technology (i) how these soils can manage the pollution?; (ii) what is the evolution of the remediation system in these polluted soils?; (iii) how nature reclaimed its rightful place, and (iv) how is the acceptance of this technique at different levels: science, politics,s and social.

2. An overview of natural attenuation

According to the United States Environmental Protection Agency [3], the natural attenuation (NA) processes include a variety of processes that reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil and groundwater. Natural attenuation takes place without human intervention. The *in situ* processes can refer to physical, chemical, or biological processes and include biodegradation, dispersion, dilution, sorption, volatilization, radioactive decay, chemical or biological stabilization, transformation, and destruction of contaminants. Monitored natural attenuation (MNA) refers to the use of NA as a remedy or management option that is based on the reliance that NA processes are able to achieve site-specific remediation or management objectives. Monitored natural attenuation should always include two essential aspects: source control and long-term performance monitoring.

It is a technique that has been used as site management and treatment technique for more than 30 years in the United States and only for a decade in Europe. The first articles on the subject appear at the end of the 1990s but the most significant publications appear in the early 2000s, which is consistent with the start of major European research projects on the subject (**Figure 1A**). Nevertheless, compared to other techniques, NA represents only an average of 5% of the techniques used for soil remediation. Phytoremediation and bioremediation represent 22% and 25% of techniques used using biological organisms whereas remediation (such as cleaning and excavation …) represents the main part with 44% (**Figure 1B**).

2.1 Role of natural attenuation in soil remediation

In 1999, natural attenuation is the “use of natural processes to avoid the spread of the contamination and reduce the amount of contaminants at contaminated sites,” following the USEPA. It can be also defined by two terms (i) bioattenuation and (ii) intrinsic bioremediation. The term “bioremediation” is used when the contaminant sources have been removed by autochtonous microorganisms from the sites or if some hot spot contaminated is removed, but can also be used when the contaminant source is still present but less toxic. Thus, natural attenuation is widely accepted in the United States and in some European countries (Denmark, United Kingdom, Netherlands,

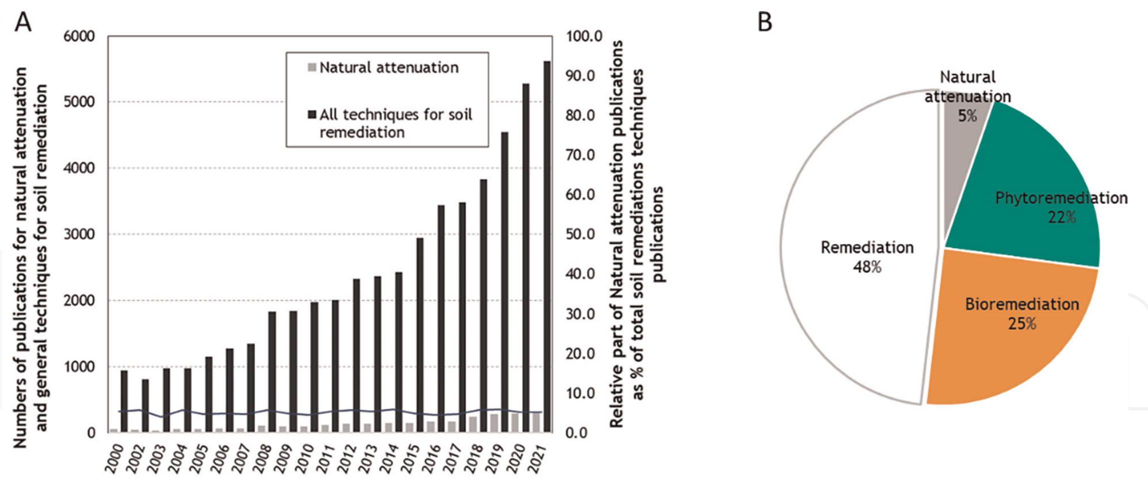


Figure 1.
A. Evolution of the number of annual scientific publications on general techniques of soil remediation (dark gray histogram) and natural attenuation (histogram light gray) in the international scientific literature over the period 2000–2021. The evolution of the relative share of publications on natural attenuation is represented by the black curve, which is estimated as % of the total number of publications on general techniques of soil remediation. B. Proportions of each technique during soil remediation over the period 2000–2021. Bibliometrics on the state of scientific and technological knowledge on natural attenuation technique has been evaluated with two search engines: Web of science and Medline, using these keywords "natural attenuation," "remediation," "phyroremediation," and "bioremediation" with different combinations.

Belgium, Germany …) as a management option for contaminated soil [4]. Indeed, soils have a healing capacity with negative feedback mechanisms permitting the reinstallation of an optimal equilibrium in element cycling and an acceptable habitat for the biota. In addition, high diversity and flexibility of the biota are required to ensure the adaptation to actual conditions. Indeed, the biota has a constant lack of nutrients thus even contaminants may serve as a nutrient supply for soil microorganisms. As a consequence, contaminants enter into the biogeochemical element cycling and may disappear or accumulate in the environment. All these phenomena lead to a natural buffering and balancing system. Those natural processes are involved in environmental remediation, which can decrease the adverse impacts of contaminants and the environmental risk posed to the ecosystems. Natural attenuation used in environmental remediation is considered real technologies/processes occurring in natural reactors operating with or without engineering interventions. Depending on the scale of intervention, management activity is denominated differently, such as monitored natural attenuation, enhanced natural attenuation, soft remediation, close-to-nature bio- or ecotechnologies, *in situ* bioremediation, and phytoremediation [5]. Thus, most of the processes involved are common with the other traditional methods of remediation, such as sorption, dissolution, and biodegradation, which occur during phytoremediation or bioremediation. All the processes involved in natural attenuation are summarized in **Figure 2**.

2.2 Processes implied in natural attenuation

NA processes may be classified as either nondestructive processes, which do not destroy the contaminant but transfer it to another compartment or attenuate its concentration within a compartment, or destructive processes, which destroy contaminants *via* chemical or biological processes. This classification depends mainly on the type of contaminants. The main contaminants involved in the natural attenuation

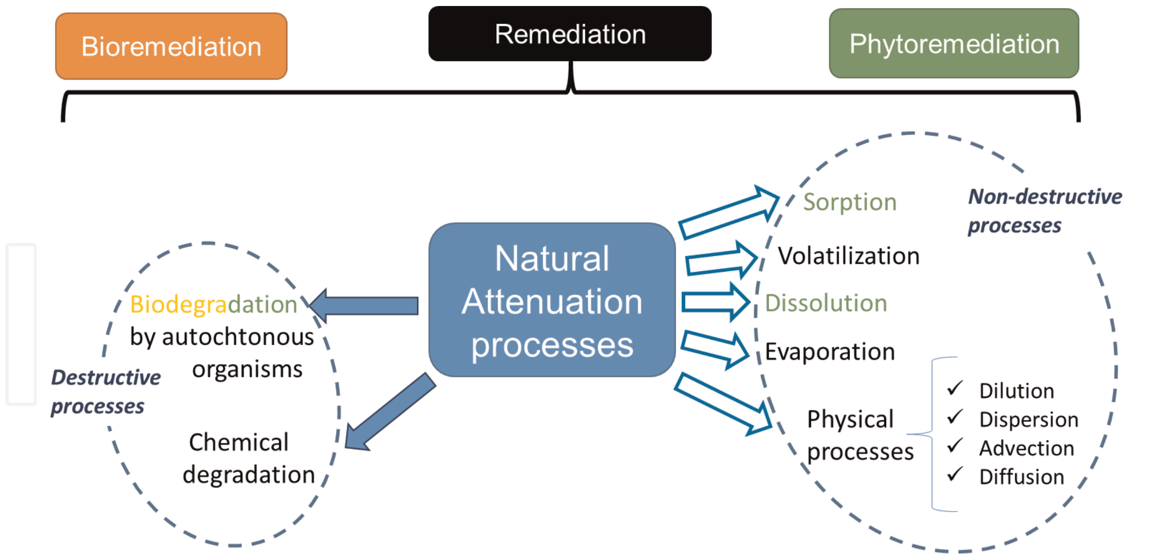


Figure 2.
Processes involved during natural attenuation and their similitude with the other common remediation techniques.

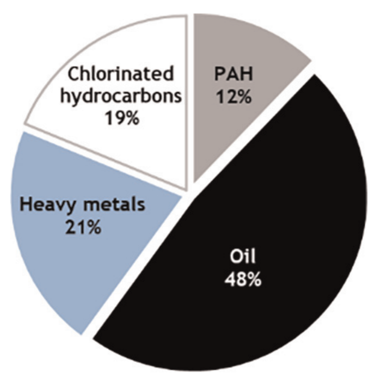


Figure 3.
Share of each pollutant treated in natural attenuation processes.

processes studied and published over the last 20 years are oils at 48%, polycyclic aromatic compounds (PAHs) at 12%, chlorinated hydrocarbons (CHC) at 19%, and heavy metals (metals and metalloids) at 21% (**Figure 3**). Oils are the primary contaminants of groundwater, while PAH, CHC, and heavy meals are the primary contaminants of soils.

Chlorinated hydrocarbon (CHC) is a generic term given to compounds containing chlorine, carbon, and hydrogen. The term can be used to describe organochlorine pesticides, such as lindane and DDT, industrial chemicals, such as polychlorinated biphenyls (PCB), and chlorine waste products, such as dioxins and furans. CHC is among the most common soil and groundwater contaminants due to their widespread use as dry-cleaning solvents and degreasing agents. These compounds are persistent in the environment and most bioaccumulates in the food chain [6]. PAHs are organic molecules with several benzene groups. Their origin in the environment can be natural (volcanic activity, formation of fossil fuels) or anthropic (industrial coal, petrochemical activity, and domestic activities). Metals are simple bodies that tend to lose electrons and differ in this respect from nonmetals. A metalloid is an intermediate element between a metal and a nonmetal. The major trace metals, because of their potential toxicity, are cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). Metals are primarily present as cations in soil water. Arsenic is the main metalloid that poses environmental problems origin of trace metals and metalloids in the environment can be natural through the weathering of rocks which leads to their release, and/or anthropogenic. Industrial activities are the main origin of soil pollution by metallic components. Thus, the fate and transport of the pollutant are controlled by the physicochemical properties of the compound itself (such as its solubility in water, its hydrophobicity, its Henry K_h constant, or its water/organic carbon partition coefficient Koc), but also by the environment (pH, redox potential, granulometry, porosity, and organic carbon content) [7].

Natural attenuation processes can be divided into four categories:

- Nondestructive processes in which the mass of contaminants does not modify within a compartment (e.g., soil solution, groundwater, or the gaseous phase): advection (transport of a quantity of a given element by the movement of the surrounding environment), dispersion (=change of direction and velocity of a particle, often related to the movements of water), and molecular diffusion (substance migrates from an area of high concentration to an area of low concentration);

- Nondestructive processes in which the mass of contaminants will change within a compartment through the different phases of the transfer processes, such as dissolution, volatilization (=change of a substance into a gaseous state), and sorption (=property that some solid bodies have to retain the molecules of other substance on their surface);

- Destructive processes: that will mainly induce a reduction of contaminant mass and discharge through biodegradation and, to a much lesser extent, chemical degradation (photolysis, redox reactions, and chemical hydrolysis);

- Nondestructive phenomena grouped under the word "dilution," which does not refer to any physical process such as the processes described above and involves mixing of polluted and non-polluted water due to the action of various phenomena (e.g., recharge by rain).

The processes involved during natural attenuation for chlorinated hydrocarbons (CHC), polycyclic aromatic compounds (PAHs), metals, metalloids, and their main characteristics are summarized in **Table 1**. CHC and PAH can completely disappear from soil because of their high biodegradation but also form a by-product of degradation that could be potentially more toxic than the parent compound [4, 8]. Whereas metals and metalloids are contaminants that cannot be degraded and will be always persistent in soil but under another chemical form (speciation), less mobile and toxic, according to their surrounding environment.

2.3 How to monitor the processes of natural attenuation?

Natural attenuation relies on natural processes to reduce or "attenuate" contaminant concentrations in soil and groundwater to protect public health and safety, and the environment. Natural attenuation is sometimes mislabeled as a "do nothing" approach to site remediation. But the truth is that natural attenuation is seen as a "proactive approach" or "passive approach" in which the verification and monitoring of the processes of natural remediation will be more concerned rather than relying

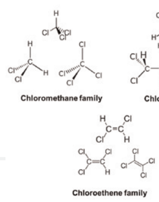
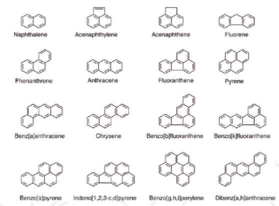
	Chlorinated hydrocarbons	PAH	Metals and Metalloids
Example of contaminants			Cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), and arsenium (As)
Fate and properties	• Low solubility in water	• Low solubility in water	• High affinity of free ions for ligands
	• High volatility	• Low volatility except for naphthalene	• Mobility influenced by pH (acid pH favors solubilization and basic pH favors their sorption) and redox conditions
	• Low adsorption except on organic matter	• Hydrophobe	
	• Biodegradabilty significant	• High toxicity	• High toxicity depending on pH and redox conditions
		• Hight persistent	• High biodissolution
Processes involved	• Dispersion		• Dispersion
	• Volatilization	• Volatilization (only naphthalene)	• Volatilization (only Hg and Se species)
	• Sorption	• Adsorption on soild phase	• Adsorption/desorption depending on surrounding environment
			• Precipitation/dissolution depending on surrounding environment
			• Dilution
	• Abiotic degradation only for 1,1,1-Trichloroethane	• Photolysis	• Neither degradation nor biodegradation
	• Anaerobic biodegradation		
	• Aerobic biodegradation only for 1,1,1 Trichloroethane and Tetrachloroethylene	• High aerobic biodegradation for PAH with a maximum of five benzenic cycles	
Results	• Complete disappearance	• Complete disappearance	• No disappearance
	• Formation of degradation products that are potentially more toxic	• Formation of degradation products that are potentially more toxic	• Decrease toxicity and immobility

Table 1.
Main fate, properties, and processes involved for chlorinated hydrocarbons, PAHs (polycyclic aromatic compounds), metals, and metalloids during natural attenuation in soils.

totally on technical processes. Before natural attenuation should be proposed for any site, the contaminant concentrations must be evaluated to document that natural attenuation is occurring by scientists or operators. It is for this reason that monitored natural attenuation (MNA) refers to the use of NA as a remedy or management option. In general, monitoring involves taking soil and groundwater samples for analysis to determine the presence of contaminants, to check for further dispersion in contaminated areas, and to assess whether there is an improvement in soil functionality. In the case of soil contaminated with organic compounds, MNA is most effective where natural processes permanently degrade or destroy the contaminants. For inorganics pollutants, MNA is most effective where immobilization or radioactive decay is demonstrated to be occurring. Many reports [9–11] have been realized concerning the monitoring of MNA in groundwater, but very few works have been dedicated to the soil. According to this literature, some parameters can be proposed for MNA in soil according to the type of pollutants:

Organics:

- Concentration and distribution of contaminants, degradation products;
- Soil geochemical parameters (e.g., electron acceptors including nitrate, sulfate, and iron (III); chloride, pH, alkalinity, oxidation–reduction potential);
- Microcosm studies demonstrating the realization of biodegradation;
- Stable isotopic tools to monitor the degradation of contaminants;
- Mass flux calculations.

Inorganics:

- Concentration and distribution of contaminants;
- Soil geochemical parameters (pH, organic carbon content, ionic exchangeable capacity, granulometry, active lime …) to determine contaminant sorption and chemical speciation;
- Data to determine the contaminant immobilization and long-term stability;
- Mass flux calculations.

Finally, experts in sciences have pointed out several indicators or lines of evidence that can be used to prove that natural attenuation processes are operating at a site and are reducing the concentrations of contaminants [4]. The first indicator is historical trends showing a reduction in contaminant concentrations at the site over time and a plume that is either stable or declining. A stable or declining plume indicates that natural attenuation processes are working well in removing dissolve contaminants from soil or groundwater; and that the amount of contaminants removed is equal to or greater than the amount of contaminants added to the plume. The second indicator is the changes in chemical parameters of soil or groundwater. The processes of natural attenuation are directly related to changes in physical-chemical parameters of the environment, such as the level of oxygen, nitrate, sulfate, and other elements because of biological consumption; and the production of by-products, such as methane. These chemical indicators can be used to evaluate the site-specific potential for contaminants to be eliminated through the processes of natural attenuation. However, if one of the first two lines of evidence does not conclude that there is natural attenuation at the site, laboratory "microcosm" tests can be set up under controlled conditions and study of living actors at the site, including plants, fauna, and in particular native microorganisms, that potentially have the capacity to degrade and absorb contaminants. The rate of contaminant destruction by the various living actors can be measured and assessed directly.

2.4 Actors involved in natural attenuation

As mentioned above, natural attenuation is used to reduce the contaminant concentration in the environment through (i) biological processes, (ii) physical phenomena, and (iii) chemical reactions. Among them, biological processes, which are carried out by different actors, including microorganisms, animals, and plants, in close interaction with environmental factors, are the dominant mechanism for the cleanup of contaminated sites. Biological processes encompass two different ways (i) biodegradation/transformation mainly led by microorganisms and (ii) adsorption/uptake done by primarily plants and animals.

2.4.1 Microorganisms

Microorganisms, including bacteria, fungi, protozoa, and algae, represent the high biomass in the ecosystems, such as soil, groundwater, and ocean [12]. Moreover, the diversity of microbial communities living on earth is high and enormous. In soil, with hundreds of thousands of taxa per gram of soil, microbial diversity dominates soil biodiversity. Thank to high biomass and diversity, microorganisms are major players that contribute to the degradation/transformation and adsorption of contaminants. The processes by which microorganisms degrade or transform the contaminants are metabolic or enzymatic actions based on growth and cometabolism processes [13]. The rate of contaminant degradation depends on different parameters: (i) type and density of microorganisms, (ii) environmental factors, such as pH, presence or absence of O_2, nutrient concentrations, temperature, and moisture, and (iii) type and concentration of contaminants. For the first point on the type of microorganisms, bacteria and fungi are known to be the most studied and the most important actors in the degradation of contaminants. There are many reports on the degradation of contaminants by different type of bacteria and fungi (**Table 2**). Yeast, algae, and protozoa are also involved in biodegradation processes but there is not much research on their involvement. Moreover, the potential of contaminant degradation by mixed microbial communities that have high genetic information is higher than by a single bacterium [27]. Numerous environmental parameters are known to be drivers determining the rate of contaminant degradation by microorganisms because the growth of microorganisms depends on these environmental parameters. Particularly, under the presence (aerobic) or absence of O_2 (anaerobic), the efficiency of biodegradation by microbial communities is different from one contaminant to another. In some cases, combined aerobic/anaerobic conditions with a consortium of microbial communities

Contaminant types		Source of pollution	Mechanisms	Microorganisms involved	References
Organic compounds	**Polyaromatic hydrocarbons (PAHs)**	industrial pollution	metabolic/ enzyme	*Pseudomonas fluorescens* *Brevibacillus* sp., *Acinobacteria* *Mycobacterium*, *Corynebacterium*, *Aeromonas*, *Rhodococcus*, *Bacillus*	[14–18]
	Chlorinated hydrocarbons	industrial pollution	metabolic/ enzyme	*Pseudomonas* sp., *Burkholderia* sp., *Ralstonia*, *Achromobacter*, *Sphingomonas*, *Comamonas*, *Rhodococcus*, *Janibacter*, *Bacillus*, *Paenibacillus*, *Microbacterium*	[19–21]
inorganic compounds	**Arsenic**	natural sources, mining and smelting, industrial processes, agriculture practices	metabolic/ enzyme	*Sulforospirillum barnesii* *Sphaerotillus Leptothrix* group *Acidithiobacillus ferrooxidans*	[22, 23]
	Lead	historic mine sites	metabolic/ enzyme	*Cladosporium* sp. *Streptomyces ederensis* *Phyllobacterium loti* *Streptomyces fulvissimus*	[24]
	Chromium (Cr)	industrial pollution	biosorption	*Bacillus marisflavi*, *Arthrobacter* sp., *Sinorhizobium* sp. *Klebsiella* sp. *Streptomyces werraensis*	[25, 26]

Table 2.
Mechanisms and microorganisms involved for chlorinated hydrocarbons, PAHs (polycyclic aromatic compounds), metals, and metalloids during natural attenuation in soils.

are applied to get better results. In general, the degradation of contaminants is carried out by the action of a cocktail enzyme that is produced by divers of microorganisms [28]. It is known that the enzyme is active in the special condition of the soil, particularly pH soil. Therefore, biodegradation of contaminants depends well on pH soil. In general, microbial degradation occurs under a wide range of pH, but high rates of contaminant degradations were found under a pH of 6.5–8.5 in most contaminated sites [29]. Contaminants are divided into two subgroups: organic and inorganic contaminants. For organic contaminants, degradative microorganisms can completely degrade organic contaminants to CO_2 or transform them into smaller compounds. Microorganisms can use organic contaminants as a sole source of carbon and energy. This mechanism results in a complete degradation, called mineralization of organic contaminants [30, 31]. On the other hand, organic contaminants are transformed into a metabolite that is less toxic. Unlike organic contaminants, the metals, inorganic compounds, cannot be degraded but may be transformed into different forms which are nontoxic or immobile or are physically available for uptake by plants or animals.

2.4.2 Plants

Besides microorganisms, plants play also an important role in natural attenuation processes. In the contaminated sites, plants can develop different strategies in order to survive and thrive; therefore, plants must principally exhibit: (i) fast growth, (ii) high tolerance to one or cocktail of contaminants, and (iii) the ability to produce and secrete a different enzyme to assimilate, transform, metabolize, detoxify, and degrade various contaminants. The primary role of plants in natural attenuation processes is to uptake contaminants from soil/water, transport them, and accumulate them in their aerial parts. Unlike microorganisms which are not easily separated from soils, the plants after having absorbed and accumulated the contaminants in plant tissues can be removed from soils and thus reduce contaminant concentrations at the contaminated sites. The plants that have extraordinary ability to uptake, transport, and accumulate contaminants in their aerial parts are called hyperaccumulators. A potential and good candidate of hyperaccumulator for adsorption of contaminants has a ratio of bioaccumulation factor and translocation factor higher than 1. It is known that the ability to uptake and accumulation of contaminants in different parts of the plants depends on (i) the density and diversity of plants, (ii) the physicochemical properties of the soil, (iii) the weather and environmental conditions, and (iv) the nature of the contaminant itself [32].

Plant species within the same genus and different varieties of the same species may exert different patterns of contaminant uptake. Moreover, the concentration of contaminants accumulated in different parts of the plants, including roots, stems, and leaves, are different. Few works also showed that a rich diversity of plants enhance the natural attenuation in the case of polycyclic aromatic compounds (PAHs) [33].

With regard to soil properties, numerous studies highlight the role of soil texture (*i.e.,* sandy, sandy clay, loamy, and sandy loam), soil chemical characteristics (*i.e.,* pH, organic matter concentration, mineral concentration, cation exchange capacity, water solubility, and O_2 presence) in the capacity of plants to uptake and accumulate contaminants. These critical factors determine the nature of contaminants in the soil, in particular bioavailability form for plants, and thus the potential for uptake by crop plants [34]. In addition, some works [35] showed that in aerated soils, plants grow better than in non-aerated ones due to high respiration and good root functionality in the rhizosphere zone, better uptake of water and nutrients, and therefore better contaminant adsorption. Moreover, meteorological factors, such as ambient temperature, humidity, and wind speed may affect the adsorption of contaminants by crop plants by shaping the rate of evapotranspiration and thus the uptake of water, nutrient, and contaminants.

2.4.3 Soil fauna

In soils, in general, soil fauna, which is characterized by large numbers of animal species, plays a central role in the ecological functions of soil ecosystems. They participate in (i) organic matter mineralization and dynamics; (ii) support and regulation of primary production; and (iii) regulation of formation and development of soil [36]. Soil fauna composes of three groups according to their size: (i) microfauna includes organisms smaller than 0.1 mm in size or diameter, such as protozoans, nematodes, and rotiphers; and (ii) mesofauna consist of organisms in size from 0.1 to 2 mm, such as Acari, Collembolan, Enchytraeida, and others; and (iii) macrofauna are classified as organisms in size from 2 to 20 mm, including earthworms, termites, and others [37]. Many works showed that the soil fauna is sensitive to environmental changes and pollution [38, 39]. In highly polluted soils, some organisms can be found because organisms have adapted to the presence of the contaminants. The impact of contaminants on soil fauna depends on numerous factors, including soil properties, the concentration of the availability of contaminants, the sensibility of species, and avoidance strategy [40]. In turn, soil fauna through their activities can influence the distribution and the availability of contaminants that can improve the process of natural attenuation. In particular, numerous species of earthworms, such as *Eisenia fetida*, *Lumbricus terrestris*, *Lumbricus rubellus,* and *Aporrectodea caliginosa,* can survive in soils polluted with metals and even accumulate heavy metals, including Cd, Pb, Cu, and Zn [41]. The activities of earthworms were shown to increase the availability and mobility of heavy metals (*i.e.,* Cd, Pb, and Hg) [42–46]. Apart from earthworms, very few data have been demonstrated on the application of other soil fauna in the processes of natural attenuation.

2.4.4 Interaction between plant-fauna-microbe-soil

As we have shown above, in contaminated soils, the main actors that play a dominant role in the natural attenuation process are the microorganisms *via* their activities involved in the degradation of contaminants, and the plants *via* their capacity to uptake contaminants. However, it is important that, under real conditions, often in the presence of a cocktail of contaminants, the complexity of the interaction between plant-fauna-microorganisms under the influence of soil physicochemical parameters must be taken into account. The interactions between plants-microorganisms-fauna that can have an impact on the natural attenuation have been proposed and presented in **Figure 4**. The positive influences of vegetation, including habitat formation and root exudation production on microbial communities, have been already demonstrated in numerous works [47, 48]. An astonishing number of microbes are able to colonize plant

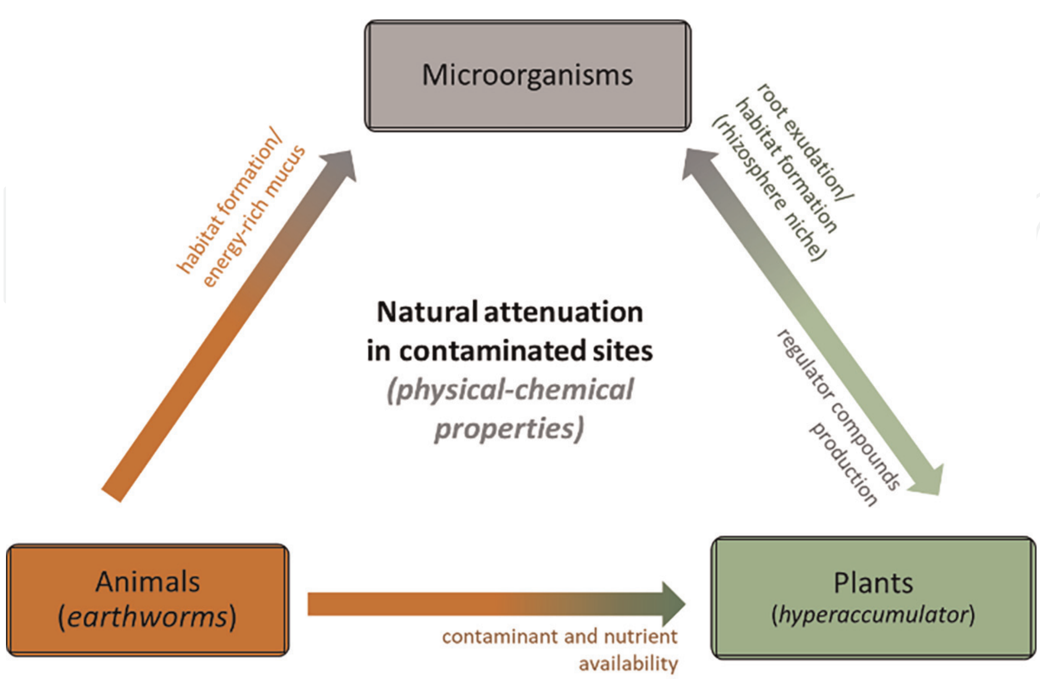


Figure 4.
The hypothesis of synergic relationships between soil-plants-animals-microorganisms in the process of natural attenuation at the contaminated sites.

roots very efficiency, forming the rhizosphere niche. In rhizosphere niche, microorganisms are equipped with many mechanisms to overcome toxicity and contribute to bioremediation. The mechanisms are (i) bioaccumulation in which microorganisms take up and accumulate contaminants in their cells, (ii) biotransformation in which contaminants are transformed into other less toxic compounds, and (iii) biosorption in which contaminants bind with cation-binding proteins present in the cell wall of microorganisms [47]. Root exudates produced by plants are organic acids, sugars, hormones, amino acids, vitamins, enzymes, and other types of primary and secondary metabolisms, which act as a source of nutrients for microbial growth and development. In other cases, some root exudates also prevent the growth of harmful microorganisms in plants [49]. They also play a significant role in bacterial quorum sensing and biofilm formation [50]. These lead to improve and increase the potential of microbial remediation. The interaction between the plant and the microorganisms is high complete. As cited above, plants help microorganisms to grow and resist contaminant toxicity, and on the other hand, microorganisms have positive and negative impacts on the plant. In general, rhizosphere microbiome consists of mainly beneficial bacteria and fungi that can have an impact on plant development. In fact, plants in retour can benefit from the production of regulator compounds called siderophores through the activities of rhizosphere microbiome to resist the toxicity of contaminants and to better grow in contaminated soils. The beneficial effects of siderophores produced by rhizosphere microorganisms on plant growth have been demonstrated in various works [51–53]. For example, the microbial produced-phytohormones by plant growth-promoting rhizobacteria (PGPR) promote plant growth and modify root architecture with an increase in root surface area leading to an increase of nutrient and contaminant uptake [54]. According to recent research, the utilization of PGPR for remediation is becoming a good strategy thanks to its various abilities to detoxify and degrade toxins, as well as its significant effects on plant growth promotion. Numerous bacteria, such as *Pseudomonas* sp., *Burkholderia* sp., *Bacillus* sp., *Bacillus* sp., *Penicillium* sp., *Streptomyces* sp., and *Endophytic* sp. are identified as the rhizobacteria species responsible for stress tolerance to organic and inorganic (heavy metals) contaminants in crop plants [53, 55, 56]. In conclusion, when the plants grow better, they can uptake more contaminants and thus increase the efficacy of the natural attenuation process. Regarding the soil fauna, among them, earthworms are known for their capacity to survive in contaminated soils and have many contributions on microbial growth through their activities, such as habitat formation (drilosphere zone) and support nutritional resources *via* the excretion of mucus [57]. On the other hand, earthworms can improve the soil's physical and chemical properties and increase the soil fertility through amelioration of microbial activities. Furthermore, according to the results demonstrate in many works, earthworms increase the bioavailability of inorganic contaminants (heavy metals) in soils, which is a primordial factor controlling the success of phytoremediation. Readers can find more information on the mechanisms direct and indirect of earthworms effect on soil microorganisms and plants in the paper published by Jusselme et al. (2020, 44]. So, high microbial growth and development thanks to the contribution of soil fauna (earthworms) may enhance the efficacy of the natural attenuation process in which microorganisms contribute to the degradation/transformation and adsorption of contaminants. Moreover, the activities of earthworms (soil fauna) are known to enhance the availability of nutrients as well as contaminants for plant health and development and also contaminant uptake by the plant. This leads to an increase in the potential of plants for the remediation of contaminants.

2.5 Factors enhancing natural attenuation processes

Remediation by enhanced natural attenuation (RENA) refers to an enhancement that can be done in soils to increase the degradation or sequestration of contaminants beyond what occurs naturally without our intervention [58–60]. In general, enhancements must be used at one time in order to maintain their effectiveness which involves a favorable balance between mass flux and system attenuation capacity. Most of the works for RENA are focused on organic contaminants and groundwater. Nevertheless, according to this literature, it is possible to give some examples of enhancement and their effectiveness. Thus, enhancement can involve improving nutrient, aeration, and moisture content for an *in situ* bioremediation approach, which has recorded many successes toward pollutant removal [58] in order to increase the biodegradation of organic pollutants. Moreover, some studies [60] have shown that the addition of an amendment can stimulate a natural consortium of bacteria to improve the degradation rate more effectively than without it. Natural consortia of microbes with additional species can be also added to increase the overall degradation of contaminants. Finally, sorption is another attenuation process that is possible to enhance by augmenting the stable fraction of organic carbon. Some natural attenuation processes cannot be implied for enhancement, especially in soil. For example, diffusion and dispersion are processes that cannot be feasible to increase.

2.6 Application and advantage/inconvenient of natural attenuation

Some countries have gained in experiences these last decades, especially the United States. Some European countries, such as Denmark, Netherlands, Belgium, Germany, and Sweden, had also developed for the first time some programs at the beginning of the 2000s. The purpose of these programs was to develop the protocols and real applications of MNA [4, 61]. These works published a review of different MNA concepts in those countries and provide an updated overview of the differences and similarities between them, with special attention to the return on experience and legal frameworks.

Nevertheless, there are numerous guides and protocols with the number increasing each year. It should be noted that these organizations do not have a common methodological tool for site management, which may explain the multiplicity of these protocols. A protocol can be defined as a strategy plan, a methodology to be followed for the proper use of natural attenuation as a rehabilitation technique. In general, three steps are always identified in the identification of the natural attenuation potential at a contaminated site:

- Development of conceptual models of the site hydrogeology and biogeochemical reactions at the site;
- Analysis of the measurements made on the site in order to quantify the natural attenuation processes (spatial and temporal evolution of the contaminants and their footprints);
- Establishment of a long-term monitoring program to verify the expected results.

All these studies and experiments have highlighted several advantages using when using monitored natural attenuation, such as low costs, minimal disturbance, and

Advantages	Disadvantages
• Overall costs are lower than other techniques.	• Longer periods of time may be required to mitigate contamination.
• Minimal disturbance to the site operations.	• Natural attenuation is not appropriate where imminent site risks are present.
• Potential use next and below buildings.	• Despite predictions that the contaminants are stationary, some migration of contaminants may occur.
• No generation of remediation wastes.	• Institutional controls may be necessary to ensure long-term protectiveness.
• Reduced risk of human exposure to contaminants near the pollution source.	• More efforts may be required in order to gain public acceptance of natural attenuation.
• Complete destruction of organic contaminants through biodegradation processes.	• Intermediates of biodegradation may be more toxic than the original contaminants.
• Stabilization of metals and metalloids.	• Some inorganics contaminants can be immobilized, such as metals, but they will not be degraded.

Table 3.
Advantages and disadvantages of monitored natural attenuation.

efficiency. Nevertheless, there are several limitations [3, 8, 62, 63] such as the long time periods before to mitigate contamination, the zero risks do not exist, and a lack of some data to model this process. All these advantages and disadvantages are displayed in **Table 3**.

3. Soil remediation by natural attenuation: What social acceptability?

Social acceptability has become a new decision-making standard for many development projects [64]. This concept gives rise to terminological debates [65], however, it can be defined as "the result of a process by which the parties concerned construct together the minimum conditions to be put in place, so that a project integrates [...] in its natural and human environment, [...] agreed in full knowledge of the facts by all the parties in a climate of fairness between the various experts." It is a question of finding acceptable reasons to justify a collective action that appears to be the best solution, including the status quo. This approach, therefore, implies taking into account the perception of public opinion, which conditions the appropriation of the project [66]. While the European Commission has presented a strategy in favor of soils, of the restoration and protection of soils by 2050, (knowing that 70% of them are degraded) [67], lifting the invisibility of soil pollution appears to be a prerequisite before considering the social acceptability of remediation projects and techniques to be preferred. It will then be necessary to consider the conditions for sociopolitical, community, and economic acceptability [68].

3.1 Invisible soil pollution?

3.1.1 A lack of scientific and technical knowledge

The distinction between healthy and polluted soil is made on the basis of the level of acceptable risk to the populations of the environment; this is specifically standardized by each society [69]. Moreover, the issue of polluted soil entered very late (1980s), in the environmental codes of the various European countries [70], whose pollution of certain regions was obscured and "sacrificed" to industrial development [69]. The soil has recently been the subject of particular attention [70]. The latest estimates for the EU28 show 2.8 million polluted plots [67], yet only about a quarter of these sites are included in databases. BASIAS and BASOL in France listed between 300,000 and 400,000 contaminated sites in 2006 [71]. In addition to the lack of knowledge in this area, there is a lack of information about the presence of pollution and its exact nature. This invisibility allows the problems associated with the implementation of clean-up projects to be hidden at different levels of decision-making and responsibility (land management, evolution of the activities concerned, public opinion...). The polluter-pays principle at the heart of the crucial question of costs requires defining responsibilities for contamination that often goes back several decades. Finally, the management of soil pollution has been done, for a long time, in a silent way in an inter-society between regulators, polluters, and engineers [67]. Moreover, the legislation concerning polluted soils in the European Union remains very fragmented.

3.1.2 Making soil pollution invisible: A pragmatic approach?

Soil and water pollution affects many territories with an industrial past and raises issues that are as much health-related (exposure to risks), socioeconomic (inequalities in terms of this exposure to risks, precariousness of employment areas, etc.), as symbolic (stigmatizing and potentially repulsive image for the establishment of companies) and, of course, political (management of costs, application of the polluter pays principle, policy of reconversion of territories, etc.) [71]. The success of an industrial reconversion implies, first of all a landscape reconstruction that hides the traces of the past. The invisibilization of pollution can be considered as the decision to "deal with" it, failing to eliminate it. Thus, in the Swansea Valley in Wales, the choice was made to leave the polluted soil on site and cover it with an impermeable material [67]. Physically concealed and polluted soils are no longer considered a problem for the redevelopment of contaminated sites. These camouflage strategies also involve the revegetation of polluted sites in order to make them landscape-pleasing and therefore potentially attractive [ibid]. The economic reconversion of certain sites (hosting businesses, tourism development, heritage enhancement, etc.) can thus lead to an invisibilization of the memory of the risk and of the pollution deemed the most embarrassing [72]. The removal of polluted soils can contribute to another form of invisibilization. Thus, soils evacuated to the outskirts of Paris during the remediation of various neighborhoods in the nineteenth century have been reintegrated into the contemporary urban fabric for the implementation of development projects and green spaces [73]. In the Nantes region, waste rock from mining sites has been moved to be used as a fill for development operations (roads, community facilities, and buildings) [74]. In addition, some wastes are stored in geological layers and others are outsourced to African and Asian countries. The concealment is also of a semantic nature, particularly in public discourse [75, 76]. Local elected officials, like some companies, seek first to reassure populations about the environmental and health impacts of polluted soil. Faced with a lack of technical and financial means, but also with political, economic, and electoral stakes, they may opt to minimize the problem.

3.2 Levers for making pollution visible

3.2.1 Visibility led by NGOs and citizens' movements?

Public actors play a real role in the reporting of soil pollution [73, 77], however, NGOs and citizens' associations often constitute the levers of its visibility. The first national policies in Europe were envisaged after the denunciation by militant associations (Green Peace, Robin Hood, Legambiente) of serious industrial incidents (toxic landfill of Lekkerkerk in the Netherlands, Seveso accidents in 1976, Chernobyl and Schweizerhalle in 1986) [78]. Specifically involved in the field of the environment on a national or international scale, or created in a specific context on a local or national scale, they endeavor to publicize the risks associated with pollution, to inform and raise awareness among populations that are sometimes unaware of or refuse to admit the dangers they face. Thus, the NGO France Nature Environment attempted in 2017, to mobilize the public around a European citizen's initiative called "L'Appel du sol" [67]. The actors who mobilize may come from intellectual professions with strong social and cultural capital, but previous participation in union organizations or protest movements may be a driving force, regardless of social category [75]. The visibility of pollution can be initiated by long-established residents who know the history of the site. However, the installation of new residents, in search of a pleasant living environment, encourages the denunciation of nuisances and the highlighting of an environmental heritage that is sometimes obscured by the older residents. The visibility of polluted soils corresponds to urban as well as rural contexts, land valuation, protection of spaces, promotion of new uses, and of sociological renewal (gentrification). When the "official" scientific studies are insufficient or instrumentalized, and/or the pollution is hidden, the groups involved in these actions set up their own expertise: field surveys, data collection, technical training, and collaboration with scientists. Their approach also involves publicizing their actions in order to put pressure on the public authorities and to enter into a more global framework of environmental activism by getting closer to other groups engaged in similar approaches.

3.2.2 Resilience and environmental justice: Mobilizing concepts

Originating in ecology, adapted to psychology, and then mobilized by the social sciences [67], the concept of resilience has become a dominant reference for territorial action. The term "territorial resilience" translates the "ability of certain territories to generate within themselves, capacities of resistance and adaptation to change, thus allowing them to maintain or recover the bases of their development and their specificity in the face of more or less brutal shocks" [79]. This is a concept used in cindynics, associated with abrupt events and their management. Soil pollution invites us to question the resilience of the sites concerned over longer timeframes and to question a latent risk. Moreover, the virtuous character attributed to the concept of territorial resilience must be put into perspective. Thus, territorial resilience operations such as the one carried out in the Swansea Valley previously mentioned [77], do not imply the elimination of pollution and associated risks. Moreover, the mobilization of this concept of resilience tends to polarize the debates on the only local capacities of adaptation to socioeconomic and environmental changes without questioning the structural causes; this annihilates any reflection on the issues of territorial inequalities and environmental justice. Resilience is then seen as an incentive for local actors to adapt by their own means in a context of state disengagement.

Not all territories are equal in their capacity to adapt. Resilience operations favor potentially attractive territories, where the cost of soil decontamination can be assumed thanks to high profitability of land and real estate. These issues have been raised by research on the concept of environmental justice [80]. They highlight the link between exposure to a degraded environment and belonging to disadvantaged social categories [81] and ethno-racial minorities. The case of the city of New Haven studied and mapped [82] is edifying in this respect. More generally, the transfer of waste from the centers to their margins or from urban spaces to agricultural spaces is indicative of this environmental injustice, whose denunciation initiated in the 1970s in the United States [83] does not stop mobilizing.

3.3 Acceptability of the clean-up process and technical choices

3.3.1 Soil remediation through the lens of ecosystem services

The acceptability of soil remediation projects depends on the benefits known to society and the value attributed to them. The social benefits can therefore be considered through the prism of ecosystem services. This concept has been mobilized and widely publicized by the Millennium Ecosystem Assessment (2015); the objective was to promote the protection of ecosystems by assigning economic and social value to the services provided by them [84]. Ecosystem services can therefore be defined as the benefits provided by ecosystems to human societies. A distinction is made between production (or supply) services, regulation services, and cultural services [84]. Despite the reservations which are made by ecologists and sociologists among others with regard to this concept and the reflections as to a “commodification of nature” [85], this can be useful here to consider the potential economic and social benefits of the soil remediation, particularly with natural attenuation. The most directly perceptible benefit for the population is undoubtedly landscape and esthetic. The decontamination of polluted sites can on radically modify the urban landscape and the image of districts or cities sometimes stigmatized by their industrial or mining past, and thus procure an embellishment to which the local populations are sensitive [65]. The revegetation of these soils can provide spaces for relaxation and leisure. In this sense, these are the benefits associated with cultural services that can be highlighted. Soils also provide regulatory services. In the context of sustainable city projects, soil remediation can contribute to the objectives of reducing greenhouse gases and improving air quality. Soils and plants store carbon in their tissues via photosynthesis, and participate in the maintenance or dissemination of a certain diversity of biodiversity, (biodiversity of soils is too often unknown), and can be integrated into larger projects for the maintenance or development of biodiversity. The greater permeability of these soils is an asset to limit the runoff and potential flooding in certain cases and restoration of the water cycle more generally, including filtering and purification functions, provided by soils and vegetation [44]. Soils also provide production services; they are the basis of agricultural activity and contribute to product quality. The assessment of these social and environmental amenities provided by soils remediation projects are, however, for the most part, complex to assess and account economically, in particular regulation and cultural services. The monetary calculation of the direct or indirect services rendered could however minimize the costs of soil rehabilitation projects and facilitate their wider implementation. In a context of scarcity and overbidding of land, the remediation, restoration, and then requalification of these soils is a real challenge [71]. The SES approach implies choices regarding the policy to be implemented. Should the multifunctionality of soils be preserved whatever the current use of the land? This is the preferred option in the Netherlands. Should the soil functions to be protected and is identified according to the current land use and its possible use? Canada and the Flemish region in Belgium are moving in this direction [Nowak 2003].

3.3.2 The acceptability of the techniques chosen: A question of perception and interpretation by the actors concerned

The perception of these remediation projects, by the population concerned is influenced by multiple factors: first, the identification of the risk associated with soil pollution and the potential benefits expected from natural attenuation. This identification is closely linked to knowledge of the health risks involved. It was highlighted in a Quebec mining site, that the knowledge by all of strong soil pollution, whose effects on the health of populations are clearly highlighted, facilitates the acceptance of soil remediation projects. In this case, the benefit is clearly identifiable, so the populations are extremely favorable to a method of depollution considered as ecological [86]. However, it is not necessarily the case in urban areas where pollution is old and associated with activities considered to be less polluting. Thus, the spreading of Parisian mud on the fields of farmers located in the immediate suburbs of Paris in the nineteenth century was not initially considered as a polluting activity [87]. In addition, the renewal of the population in a good number of urban regions leads to a lack of knowledge of the history of soils and associated pollution. In most cases, the esthetic and landscaping criteria have an essential role in the reception that can be given to this type of project [88]. The remediation of soils in neighborhoods where the image is devalued by an industrial or mining past constitutes a benefit clearly identifiable by the population who have been living there for a long time or more recently. Revegetation of the soils is particularly often equated with embellishment and an improvement of the living environment from an ecological point of view. Consultation on the landscapes desired by local residents requires a time of information and consultation that is added to the time necessary to obtain the first effects of the different soil remediation methods. In this regard, it should be emphasized that local communities such as companies specializing in soil treatment are often ill-informed and poorly trained or little trained in this type of alternative techniques and prefer to apply better known and better-controlled methods, such as excavation and backfilling of polluted areas. It seems that alternative remediation, particularly natural attenuation, is struggling to get out of the purely scientific and experimental sphere. In terms of costs, *in situ* alternative natural treatment is a much less expensive technique than conventional techniques, however, it still seems to be little applied [89]. The low use of these treatments can be explained by a lack of knowledge, lack of experience, uncertainty about treatment effectiveness, uncertainty about cleaning performance, and the longer time usually needed for *in situ* remediations. The time required to obtain significant results is a constraint both for development companies, local authorities, and for the population. In the Netherlands, the tolerated duration of soil treatment by AN is about 30 years; in the United States, the duration beyond which another technical choice will be preferred is not fixed; it must be "reasonable" [7]. The results must be perceptible to the residents, who must be reassured by precise information on the progress of the treatment phase. In the process of acceptability of natural attenuation, an articulation between these different temporalities constitutes an issue to be taken up.

4. Conclusions

Natural attenuation and monitored natural attenuation (MNA) use the natural capabilities of microorganisms in close interaction with plants and fauna at the site to degrade contaminants as well as the geochemical immobilization and NA processes in the environment. MNA can be an efficient, green, and sustainable approach for contaminated soil remediation when the source of contamination is controlled and when potential risks for human and ecological systems can be managed in an acceptable manner. In general, MNA alone may be unable to reach cleanup goals within a reasonable timeframe, therefore MNA is often associated with other remediation methods. Its use should be most favored within vulnerable habitats where the implementation of other remedial activities might cause additional unacceptable environmental damages.

Conflict of interest

The authors declare no conflict of interest.

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