INTRODUCTION TECHNOLOGY WATCH REPORT: CONTAMINATED SOIL REMEDIATION TECHNIQUES

The first part of this technological report describes pollutant agents and contaminated soil remediation techniques. In the second part, there are information related with the state-of-the-art of this sector, including up-to-date information on Spanish and European R&D projects, scientific publications, and technologies patented.

INTRODUCTION

Soil, the uppermost layer of the earth's crust, is one of the most important natural resources that exist since it is the basis sustaining life on the planet. From a pedology perspective, soil is a three-dimensional natural body formed by the progressive physical and chemical alterations of an original parent material over time in specific climatic and topographical conditions, and is subject to the actions of living organisms. Throughout its evolution or pedogenesis, vertical columns of generally non-consolidated material are established in the soil called horizons. These horizons are made up of mineral and organic constituents, water and gases, and are characterized by physical properties (structure, texture, porosity, water-holding capacity, apparent density), and chemical and physical-chemical properties (pH, redox potential, cationic exchange capacity) which differentiate them from one another and from the original parent material. This collection of horizons constitutes the soil's profile and its study allows the formation processes undergone during its evolution to be clarified and also allows it to be classified within the different soil taxonomies.

Soil's importance lies in that it is a dynamic, living, natural element. It is the interface between the earth's atmosphere, lithosphere, biosphere, and hydrosphere; systems with which it continuously exchanges matter and energy. This makes soil key to the development of surface biogeochemical cycles and gives it the ability to perform a series of essential functions (environmental, ecological, economic, social, and cultural) within nature:

- Soil provides the nutrients, water, and the physical environment necessary for vegetative growth and for the production of biomass in general, playing a fundamental role as a food source for living creatures.
- It is an essential component of the hydrologic cycle, acting as the distributing agent for surface water and contributing to groundwater storage and recharge.

- Soil, through its buffering capacity or its role as a natural deactivator of contamination, filters, stores, degrades, neutralizes, and immobilizes both organic and inorganic toxic substances, stopping them from reaching the groundwater or the air or from entering the food chain.
- It is the biological natural habitat of a number of various organisms and constitutes a genetic reserve element.
- It plays a fundamental role as a source of raw materials.
- A pillar of the socioeconomic structure, soil serves as a platform for the development of human activities, forming part of the landscape and the cultural heritage as well.

Soil is a fragile element of the environment. Since its rate of formation and regeneration is very slow compared to the processes that contribute to its degradation, deterioration, and destruction, soil is a non-renewable natural resource. For this reason, public awareness must be raised on this topic and environmental and political measures need to be put into places that guarantee soil protection and conservation.

According to FAO-UNEP (1983), soil degradation can be defined as any process that reduces the current and potential ability of the soil to quantitatively and qualitatively produce goods and services. Although natural causes can lead to soil degradation, it is fundamentally a direct result of mankind's use of soil either through direct actions such as agricultural, forestry, livestock, agrochemical, and irrigation purposes, or through indirect actions like industrial activity, waste removal, transportation, etc. These degradation processes can be classified according to their nature and the type of negative consequences they have on soil properties: biological, such as the depletion of a soil's organic matter content; physical, such as the deterioration of the soil's structure as a result of compaction and increased apparent density, lower permeability and water-holding capacity, or soil loss through erosion; and chemical, such as the loss of nutrient elements, acidification, salinization, solidification, and increased toxicity. These latter consequences are included in the term pollution.

SOIL CONTAMINATION

Soil contamination consists of a chemical degradation that leads to the partial or total loss of the soil's productivity as a consequence of the accumulation of toxic substances at concentrations that exceed the soil's natural buffering capacity and which negatively modify its properties. This type of accumulation is generally the result of exogenic human activities, although it can also occur naturally or endogenically when formation processes release the chemical elements contained within rocks, concentrating them in the soil until toxic levels are reached. An example of this can be found in much evolved soils formed on top of serpentinized rocks with high levels of heavy metals such as Cr, Ni, Cu, and Mn, among others, which are concentrated in soils while the intense pedogenesis washes away other essential constituents like Ca, Mg, and even Si. As this residual metal concentration rises, those elements that were initially non-assimilable constituents of the primary minerals become more active, soluble, and bioavailable forms that negatively influence biological activity (Macías, 1993).

As was mentioned above, the physical, chemical, physical-chemical, and biological properties of soil primarily control the surface biogeochemical cycles, acting as a complex reactor that serves as a means of protection for other mediums that are more sensitive to contaminating elements. Soil, thus, exercises its protective powers through its **buffering capacity** or natural ability to filter contamination. Harmful contaminating elements are reduced, among other ways, through complexation reactions, adsorption and desorption reactions, precipitation and dissolution reactions, oxido-reduction reactions, acid-base reactions, and reactions derived from metabolic processes. All of these reactions are closely controlled by soil properties including its texture, structure, porosity, cationic exchange capacity, pH, Eh, and microbiological activity. In any case, one must realize that a soil's buffering capacity is not unlimited and when it is exceeded, the soil ceases to be an effective contamination sump, sometimes to the extent that the process is inverted, becoming instead a source of contamination for the organisms in the soil and for the surrounding mediums.

When studying soil pollution, it is not enough to simply detect the presence of the contaminating substance or substances. Its concentration must surpass the **critical charge** or maximum allowable amount in soil without producing harmful effects that cannot be counterbalanced by the soil's buffering capacity. It can thus be concluded that different soils will react differently in the presence of the same contaminant or the same amount of contaminant. This reaction will be conditioned by factors such as each soil's specific **vulnerability**, which represents the soil's degree of sensitivity in response to aggressive contaminating agents. The soil's vulnerability is also closely linked to its buffering capacity in that the weaker its buffering capacity in contact with contamination, the greater its vulnerability. Thus, each soil's degree of vulnerability with respect to contamination depends both on the intensity of the contamination and on the speed with which the negative changes on the soil's properties in response to this contamination occur. In addition, a particular soil's degree of contamination cannot be determined solely by comparing the total contaminant values with statistical tables. Rather, one must consider the **bioavailability** of the contaminant or its possible assimilation by the organisms in the soil, which is determined by the competition between the plant's radicular system, the soil solution, and the soil solid phase (Sposito, 1989); its **mobility**, which regulates its distribution and transportation within the soil or to other mediums; and its **persistence**, which determines the duration of the contaminant's harmful effect on the soil. All of these concepts allow the potential risks of certain contaminating activities to be evaluated and to plan actions depending on the type of soil, though it must be emphasized that the soil's own heterogeneity can, in many cases, obstruct the characterization of these parameters.

The potentially contaminating agents of soil are fundamentally associated to derivative industrial, mining, agricultural, and livestock waste.

The main contaminating agents of soils are:

- Heavy metals
- Acid rain
- Salinization
- Phytosanitaries
- Mines
- Organic contaminants

REMEDIATING CONTAMINATED SOILS

In the last few years, a considerable amount of research has been focused on trying to remediate contaminated soils instead of destroying them. Soil destruction is generally carried out by taking the soil to properly isolated and controlled disposal sites when it is felt that other remediation methods cannot guarantee that the contamination will be contained.

A wide range of contaminated soil remediation technologies are currently available, some of which are routinely used and others which are still in their experimental stages, designed to isolate or destroy the contaminating substances by altering their chemical structure often times through chemical, thermal, or biological processes. The application of these technologies depends on the characteristics of both the soil and the contaminant, on the desired effectiveness of each method, on their economic viability, and on the estimated time they take to produce results (Reddy *et al.*, 1999). Depending on how the soil remediation techniques are applied, the term ***in situ*** treatments is used when they act on the pollutants at the contamination site, and ***ex situ*** when the soil must first be excavated for its subsequent treatment at the same location (on-site treatment) or at external facilities that require the contaminated soil to be moved (off-site treatment). In situ treatments require less handling but, in general, are slower and more difficult to put into practice given the difficulty of exposing the decontamination agents to the entire contaminated soil mass. Ex situ treatments are usually more costly but faster, usually achieving a more complete remediation of the affected area.

Depending on the desired objectives when remediating contaminated soil (Kaifer *et al.*, 2004), the options are:

- **Containment techniques**, which isolate the contaminant in the soil without acting on it, generally through the use of physical barriers on the soil itself.
- **Confinement techniques**, which reduce the mobility of the contaminants in the soil to keep them from migrating, acting directly on the physical-chemical conditions in which the contaminants are found.
- **Decontamination techniques**, which are aimed at reducing the concentrations of the contaminants in the soil.