



Algerian People's Democratic Republic
Ministry of Higher Education and Scientific Research
Faculty of Sciences
Department of Agronomic Sciences



Level: Second Year in Agricultural Sciences

Course materials: Agronomy 1

For use by second-year students in Agricultural Sciences

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Semester: 4th Semester

UE (Teaching Unit)

Fundamental Teaching Unit 1

Subject 1: Agronomy I (Water, Soil)

Teaching Objectives:

The student should understand the concepts and terminology related to water and different types of soils, methods of study and analysis correlated with various ecosystems.

Recommended Prerequisite Knowledge:

(Succinct description of required knowledge to follow this teaching - Maximum 2 lines).

Tutorials:

1. Relationships between measurement units used in soil sciences (Review and exercises on methods for preparing analysis solutions; unit conversion exercises).
2. Exercises on the physical aspect of soil (three-phase system).
3. Slideshow session (different soil types according to CPCS and USDA classifications).

Practical Work:

1. Mechanical analysis of soils (textural triangles).
2. Soil moisture and pH measurement and density measurement.
3. Total limestone content determination (Calcimetry) and/or organic matter content determination.

Assessment Method:

Continuous assessment and semester examination.

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Chapter 1. The Soil

1. Definition of Parent Rock

Rocks, essential materials of the Earth's solid crust, form a hard mass of mineral matter comprising one or more minerals.

Derived from magma, their weathering contributes to soil formation, thereby constituting the Earth's superficial mineral layer.

1.1. Study of Rocks

1.1.1. Sampling

Proper **sampling** techniques are vital for obtaining representative rock materials, particularly when the goal is to examine how rocks contribute to soil development.

The approach to sampling depends on the type and stability of the material being studied. For **cohesive** materials, such as compact rocks or firm soils, the sampling process can involve cutting blocks directly from the profile.

These blocks are carefully handled and wrapped in materials like **newspaper** or **plastic film** to maintain their integrity.

It is important to clearly mark the upper and lower orientations of the sample, as this ensures accurate analysis of the material's structure and layering when it is studied later.

In cases where the materials are less stable or more **loose**, such as sandy or gravelly soils, **Kubiena boxes** are often used.

These are specialized containers designed to preserve the shape and orientation of the sample during transportation and analysis. Kubiena boxes provide a stable environment for the sample, ensuring that it remains intact despite the fragility of the material.

While Kubiena boxes are effective, they can be expensive.

Therefore, **cheaper alternatives** are sometimes used, especially in educational or field research settings.

For example, **recycled cardboard boxes** such as those used for tetra packs can be repurposed to hold the samples. These boxes offer a cost-effective solution, though they may not be as durable or airtight as specialized containers.

Additionally, **plastic boxes** designed for soil sampling are another alternative. These plastic containers are lightweight and flexible, making them a practical choice for various types of soil materials.

For more **unstable or loose** samples, pre-cut blocks of soil can be stabilized by wrapping them in **plaster strips**. This method involves surrounding the sample with strips of **plaster of Paris**,

which hardens and provides cohesion, preventing the sample from crumbling or losing its form during handling.

Another approach involves spreading a layer of plaster of Paris inside the sampling box before placing the soil block inside. This process helps secure the soil sample and maintain its integrity when it is eventually removed from the field for laboratory analysis.

Once the samples are stabilized and properly wrapped, they are transferred to **crates** for storage. These crates are designed to protect the samples from external damage and to provide a safe and organized way to transport the samples to the laboratory for further analysis.

The **hardening process** of plaster ensures that the samples retain their original structure and can be carefully examined to study their mineral content, texture, and other properties.

1.1.2. Preparation of Thin Sections

The **preparation of thin sections** is an essential technique in soil and rock analysis, particularly when studying the mineral composition, texture, and microstructure of soil samples.

Thin sections provide a way to examine the internal structure of materials at a microscopic level, revealing details that are otherwise invisible to the naked eye.

The process involves a series of steps that ensure the preservation and detailed analysis of the sample's mineralogical and textural properties.

1.1.2.1. Impregnation of the Soil Sample

The first step in preparing a thin section is to select a **durable material** that can withstand the mechanical processes involved in slicing and grinding.

To achieve this, the unaltered soil sample, once removed from its storage container (such as a Kubiena box), is **impregnated with a resin**.

This impregnation is carried out under **vacuum** conditions to ensure that the resin penetrates all parts of the soil sample, effectively hardening and stabilizing it.

Common resins used for this purpose include **cold-curing resin** or **diluted polystyrene**, which are compatible with the soil's composition and provide the necessary rigidity for cutting.

It is important to note that **resin** is generally **incompatible with water**, meaning that any excess moisture within the soil sample must be removed prior to impregnation.

This is achieved by **drying the sample** either **air-drying** or **oven-drying**, or by using an **acetone replacement** process.

Acetone helps to replace the water in the sample, ensuring that the resin can fully penetrate the soil particles.

1.1.2.2.Curing and Cutting the Impregnated Block

Once the resin has fully impregnated the soil sample, the material is allowed to **cure**, or harden. The curing process may take several hours or days, depending on the type of resin used.

After curing, the sample becomes firm enough to be cut into thin slices.

This is done using a **diamond saw**, which is designed to cut through the hardened material without causing significant damage to the structure.

The diamond saw is kept cool using **special oil**, which helps prevent the dissolution of the soil's mineral constituents due to heat or water exposure during the cutting process.

1.1.2.3. Grinding and Mounting the Thin Section

After cutting the sample into a slice, the next step is to **grind** the slice to achieve the desired thickness.

The thickness of the slice is typically reduced to around **20–30 microns**, which is the standard thickness for a **thin section**.

To grind the slice to this precision, a **slurry** of fine **corundum** or **diamond powder** mixed with oil is used.

The slurry acts as an abrasive, smoothing the surface of the slice and ensuring that it is thin enough to be transparent to light, allowing for detailed microscopic analysis.

Once the desired thickness is achieved, the slice is **mounted on a glass slide** of corresponding dimensions. The size of the glass slide can vary, but common dimensions range from **48 mm x 28 mm** to **180 mm x 120 mm**.

This mounting ensures that the slice remains stable during further examination and handling.

1.1.2.4.Additional Processing and Protective Cover

Once the thin section has been ground and mounted, it may be further processed depending on the type of analysis planned.

In some cases, the thin section is **covered with a very thin protective cover slip**, which helps to protect the sample and keep it in place.

This step is usually done unless specific tests, such as **staining** tests, **cathodoluminescence**, or **microprobe studies**, are planned.

These tests may require the sample to remain uncovered to preserve the integrity of the minerals and other components under study.

Step 5: Variations in the Process

While the basic procedure described above is the standard method for preparing thin sections, several **variations** exist depending on the specific research goals.

For example, some procedures involve conducting **percolation tests** using **dye agents** as a pretreatment step to identify **porosity** within the soil or rock sample.

These tests allow researchers to visualize the movement of fluids through the sample and provide important insights into its permeability.

Additionally, **fluorescent dyes** may be added to the resin during impregnation, allowing for the visualization of porosity under **ultraviolet (UV) light**.

This technique is particularly useful for studying the distribution of void spaces and the flow of water or air through the sample.

By using UV light, researchers can observe patterns of porosity that might not be visible under normal lighting conditions, providing a more comprehensive understanding of the sample's microstructure.

1.1.3. Observation

Observation is a critical step in analyzing the structure, texture, and composition of soil and rock samples, particularly after they have been prepared as thin sections.

Various methods are used to observe these thin sections, and the choice of technique depends on the level of detail required and the type of material being studied.

The primary techniques range from traditional optical microscopy to advanced ultramicroscopic methods.

1.1.3.1. Optical Microscopy

The most common observation technique is **optical microscopy**, specifically using a **polarizing microscope**, often referred to as a **petrographic microscope** in the context of rock and soil studies.

Optical microscopy is widely used due to its relatively straightforward operation and the ability to examine thin sections in detail.

The polarizing microscope is designed to detect the optical properties of minerals and their interaction with light.

When light passes through a thin section, certain minerals will show distinctive optical behaviors such as **color changes**, **birefringence**, or **extinction**, depending on their crystal structure.

This allows researchers to identify mineral types, determine their orientation, and assess the overall texture of the soil or rock sample.

In geological studies, this method is essential for understanding the mineralogical composition and microstructure of the material.

1.1.3.2. Ultramicroscopic Techniques

For even more detailed analysis, **ultramicroscopic techniques** are employed.

These methods provide a higher magnification and resolution, enabling scientists to observe structures that are far smaller than what optical microscopy can reveal.

Two of the most advanced ultramicroscopic techniques used for thin section analysis are:

1.1.3.2.1. Transmission Electron Microscopy (TEM)

TEM allows scientists to observe ultra-thin slices of a sample at very high magnification.

It works by passing a beam of electrons through the thin section, and the resulting image is formed based on the electrons that pass through the material.

TEM can provide detailed information about the internal structure of minerals, including atomic-level observations of crystal lattices and mineral inclusions.

It is often used when analyzing fine-scale structures such as nanoscale minerals or organic matter in soil samples.

1.1.3.2.2. Scanning Electron Microscopy (SEM)

SEM is another powerful tool for observing thin sections, particularly useful for studying the surface features of a sample.

Unlike TEM, which provides detailed internal images, SEM scans the surface of the sample and produces high-resolution images by detecting secondary electrons emitted from the surface.

SEM can also be coupled with **Energy-Dispersive X-ray Spectroscopy (EDS)** to gather elemental composition data from specific areas on the sample's surface.

Both TEM and SEM are complementary techniques to optical microscopy, providing a higher level of detail that is invaluable for analyzing microstructures that cannot be captured with optical methods.

1.1.3.3. Microprobe Studies

Another technique frequently used for the observation of thin sections is **microprobe studies**, particularly those involving **X-ray microanalysis**.

In this technique, thin sections are either left uncoated or coated with a thin layer of **carbon** to enhance conductivity and prevent charging during analysis.

A microprobe allows researchers to focus a fine electron beam on specific spots on the thin section.

By analyzing the X-rays emitted from these spots, the microprobe can determine the **chemical composition** of the minerals and materials present in the sample.

This technique is essential for mapping the **spatial distribution of elements** in the sample, providing detailed information on the mineralogical composition and the chemical heterogeneity of the material.

1.1.3.4. Other Accessory Techniques

In addition to the methods mentioned above, several **accessory techniques** are used in combination with thin section analysis to gain further insights into the sample's properties:

1.1.3.4.1. Micro X-Ray Diffraction (m-XRD)

This technique is used to determine the **crystalline structure** of minerals in thin sections. It works by bombarding the sample with X-rays and measuring the diffraction patterns that occur when the X-rays interact with the crystalline structures of the material.

m-XRD is particularly useful for identifying **mineral phases** and for studying the crystallography of the sample at a micro-scale level.

1.1.3.4.2. Micro Fourier Transform Infrared Spectroscopy (m-FTIR)

m-FTIR is used to analyze the **vibrational modes** of molecules within the sample.

It provides detailed information on the **functional groups** present in the sample and is particularly useful for studying organic compounds or the surface chemistry of minerals.

FTIR spectra are obtained by measuring the absorption of infrared radiation as it passes through the sample, providing insight into the molecular composition of the material.

Both m-XRD and m-FTIR are valuable tools for complementing traditional optical and electron microscopy techniques.

These accessory methods enhance the ability to identify minerals, study chemical compositions, and understand the structural properties of the sample on a molecular or crystal level.



Figure 1. Transmission Electron Microscopy (Original, 2025)



Figure 2. Scanning Electron Microscopy (Original, 2025)



Figure 3. Micro X-Ray Diffraction machine (Original, 2025)

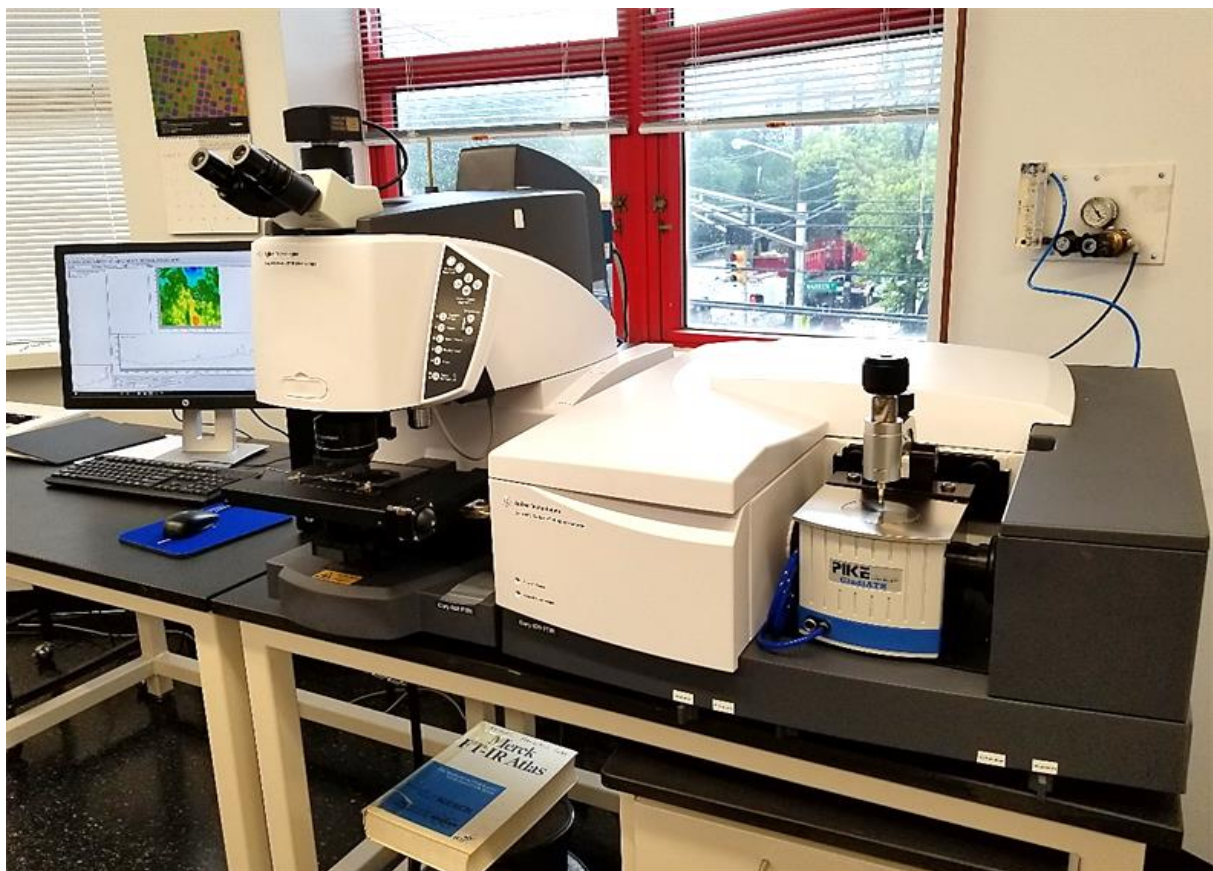


Figure 4. Micro Fourier Transform Infrared Spectroscopy (Original, 2025)

2. Definitions of Soil

Soil, an integral part of terrestrial ecosystems, constitutes the interface between the Earth's surface and the bedrock.

Resulting from the weathering and transformation of parent rock under the influence of factors such as climate, topography, organisms, time, and human activities, it is enriched by organic inputs.

It appears as a loose and organized superficial layer of the Earth's crust.

Soil serves as a reservoir of nutrients, providing a loose and friable material for plant anchorage and nutrition, and is a natural body composed of differentiated mineral and organic constituents in layers of varying depths.

Its formation results from the combined influence of climate, living organisms, and parent rock conditioned by relief over time.

It consists of a mixture of weathered rock and organic matter, supporting vegetation and serving as a zone for the exchange of nutrients, water, oxygen, and a hub for microbial activity.

Its productivity potential is reflected in its fertility, which varies according to its intrinsic characteristics. Physical processes (light exposure, hydration, desiccation, contraction) and chemical processes (dissolution, hydration, hydrolysis, oxidation, reduction) contribute to its alteration.

For ecologists, soil is a habitat and the source of numerous chemical, biochemical, and biological processes and interactions, involving the storage and dynamics of carbon and nitrogen fluxes, mineral weathering, and pedogenesis processes facilitated by microorganisms, forming an autonomous ecosystem based on vegetation.

3. The Roles of Soil

Soil plays an essential role in supporting life on Earth by providing a wide range of services that are crucial for both human development and environmental health. These functions, often termed **ecosystem services**, highlight how soil contributes to maintaining ecological balance, supporting agriculture, and enabling sustainable development. In the following sections, we will explore in greater detail the various functions and roles of soil.

3.1. Nutritional Role

Soil acts as the primary source of nutrients for plants, which are the foundation of most ecosystems and food chains.

Plant roots grow deep into the soil, where they extract vital resources for their development. These include **water**, which is absorbed through the soil and transported to plant cells, and **air**,

particularly oxygen, which is essential for respiration. The most critical role of soil in plant nutrition, however, is the provision of **mineral nutrients**.

These include macronutrients such as **nitrogen (N)**, **phosphorus (P)**, **potassium (K)**, **calcium (Ca)**, and **magnesium (Mg)**, as well as **micronutrients** like **iron (Fe)**, **manganese (Mn)**, **zinc (Zn)**, and others.

These elements are necessary for various plant functions, including photosynthesis, cellular growth, and enzyme activation.

Additionally, soil fertility, which determines the productivity of agricultural land, is influenced by factors such as organic matter content, soil pH, and microbial activity.

The **humus** in the soil holds a large portion of these nutrients, providing a long-term nutrient reservoir that supports continuous plant growth.

By supporting the health of plants, soil indirectly sustains herbivores, predators, and humans who depend on crops and natural vegetation for sustenance.

Therefore, the nutritional role of soil is central to agricultural productivity and food security.

3.2. Biological Role

Soil is a vibrant and complex ecosystem teeming with life. It is home to a variety of organisms, ranging from microscopic bacteria and fungi to larger creatures like earthworms, ants, insects, and rodents.

These organisms play critical roles in soil formation and fertility.

The soil **biota**, which includes **decomposers** like bacteria and fungi, breaks down organic matter such as dead plants and animals into simpler compounds. This process of **decomposition** is vital for recycling nutrients back into the soil, making them available again for plant growth.

Organic matter is converted into **humus**, which enriches the soil and enhances its fertility.

Soil organisms also contribute to **soil aeration**.

For instance, burrowing animals such as earthworms and moles create channels that allow air to reach deeper soil layers, improving the **oxygenation** of roots and enhancing the growth of plants.

Furthermore, **mycorrhizal fungi** form symbiotic relationships with plant roots, improving the plant's access to nutrients, particularly phosphorus, in exchange for sugars produced by the plant during photosynthesis.

Soil is also a **genetic reserve**, preserving the DNA of the diverse species that inhabit it.

This biological diversity is crucial for the long-term health of ecosystems, as it supports resilience against environmental changes and disturbances.

The biological activities occurring within the soil are, therefore, fundamental to its **fertility**, **health**, and **sustainability**, and they directly influence the productivity of agricultural systems.

3.3. Filtering and Storage Role

Soil plays a crucial role in maintaining water quality and regulating the climate through its **filtering** and **carbon storage** functions.

As water percolates through the soil during rainfall or irrigation, the soil acts as a natural filter, trapping impurities, pollutants, and excess nutrients before they can enter groundwater supplies. This **filtration** process is especially important in agricultural areas, where fertilizers and pesticides may contaminate water sources. Soil's ability to filter water helps maintain the purity of groundwater, which is a vital resource for drinking water, irrigation, and industry. Furthermore, soil acts as a **carbon sink**, storing carbon in the form of **organic matter** such as plant residues and decomposed organic material.

Plants sequester carbon dioxide (CO₂) from the atmosphere during photosynthesis, and a portion of this carbon is stored in the soil as organic matter. Soil can hold more carbon than the atmosphere and vegetation combined, making it a critical component in the global carbon cycle. By storing CO₂, soil helps mitigate the effects of climate change, preventing excess greenhouse gases from accumulating in the atmosphere.

Thus, the **filtering** and **carbon storage** roles of soil are essential for environmental health and climate stability.

3.4. Material Role

Soil is not only essential for biological processes but also for human development, as it provides various **material resources**.

These include **construction materials** such as **gravel, clay, and sand**, which are used in the building of infrastructure like roads, buildings, and bridges.

Soil's **clay** content, in particular, is valuable for producing bricks, ceramics, and pottery. In addition to construction materials, soil is a source of **energy materials**, such as **peat**.

Peat is an organic material that forms in waterlogged conditions and can be used as a fuel.

While peat extraction has environmental consequences, it remains an important resource in certain regions for heating and energy production.

Soil is also a source of **minerals**, which are extracted for various industries, including agriculture, manufacturing, and technology. Minerals such as **phosphates** are vital for producing fertilizers, while **iron, copper, and aluminum** are used in construction and electronics.

As such, soil's material role supports not only ecosystem functions but also economic activities and human livelihoods.

3.5. Archiving Role

Soil has an **archiving role** in preserving historical and environmental records.

Through its layering process, soil captures and retains evidence of past environmental conditions, **climatic changes**, and human activities. Soil layers, or **horizons**, accumulate over time, and each layer can contain information about past weather patterns, vegetation types, and even historical events such as fires or volcanic eruptions.

Archaeologists and paleontologists often turn to soil to uncover ancient human settlements and the remains of past civilizations.

Soil's **preservation** of organic materials, such as pottery fragments, bones, and plant remains, provides a window into the past, offering insights into how ancient societies interacted with their environments.

Additionally, soil's ability to store **carbon isotopes** makes it a valuable resource for studying past atmospheric conditions, including **climate history**. Thus, soil serves as a **natural archive** that holds both **natural and cultural history**, making it an invaluable tool for scientific research.

3.6. Support Function

Soil's **support function** is perhaps the most immediate and tangible role it plays in human society. Soil provides the foundation for nearly all human **constructions**, from houses and roads to larger infrastructure projects like bridges and dams.

The **physical stability** of soil is a key factor in determining whether an area is suitable for construction.

In addition to supporting structures, soil plays a critical role in **agriculture** by providing the base for growing crops, which sustain human populations.

The health and stability of the soil affect not only the crops grown but also the overall quality of the environment, as well-managed soil supports clean water, biodiversity, and climate regulation. Without soil, much of the built environment and agricultural systems we rely on today would be impossible.

4. Soil Formation

4.1. Factors of Pedogenesis

4.1.1. Parent Material or Parental Material

Different types of parent materials are listed in Table 1.

Table 1. Different Types of Parent Materials

Parent Material or Rock	Type of Soil Resulting from Degradation	Characteristics
Friable Rocks	Deep soils	<ul style="list-style-type: none"> - Penetrable by air, water, and roots. - Do not have the typical soil structure (many soil components are absent), but colonization by plants is easy.
Massive Acidic Rocks	Leached Soils	<ul style="list-style-type: none"> - Plant nutrition is deficient on these rocks, and the lack of metallic ions only allows for clay formation. - Contains a lot of difficult-to-weather quartz, resulting in sandy soils.
Massive Basic Rocks	Fertile Soils with High Cation Exchange Capacity (CEC)	- Soils resulting from the degradation of these rocks differ significantly under the influence of pedogenetic factors.
Calcareous-Magnesian Rocks	Soils with Stable Humus	<ul style="list-style-type: none"> - Rocks composed of limestone or dolomite. - Trace elements and phosphorus are in forms that are less assimilable.
Consolidated Clay Rocks	Clayey Soils	- Rocks that degrade slowly.
Saline Rocks (Salts, Gypsum)	Special Clayey Soils	- The presence of salt causes phenomena that modify the state of clays and plant physiology.

4.1.2. Climate (Water, Temperature)

4.1.2.1. Mechanical or Physical Weathering

Mechanical weathering of rock, resulting from various climatic episodes, is characterized by the appearance of cracks.

Additionally, fracture planes, oriented differently depending on the nature and origin of the rock as well as tectonic stresses, contribute to this process.

Temperature variations induce the expansion and contraction of rocks, causing constant fluctuations in their volume.

This process leads to rock cracking and eventual fragmentation.

When water enters these cracks and freezes, its volume expands, exacerbating this effect.

Ice crystals form perpendicular to the crack surface, increasing its width. Ice exerting a pressure of 14 g/cm² during freezing in a crack eventually causes rock fragmentation, a phenomenon known as frost wedging.

4.1.2.2. Chemical Weathering

Chemical weathering occurs when rainwater reacts with mineral grains of rocks, forming new minerals such as clays and soluble salts, particularly under slightly acidic conditions.

This process is intensified by temperature elevation.

4.1.2.2.1. Dissolution

Pure water dissolves gypsum, calcite, and to a lesser extent feldspar and quartz, while CO₂-charged waters significantly increase dissolution phenomena.

Dissolution reactions generate ions without forming minerals and are reversible once the solvent is removed.

4.1.2.2.2. Hydration

This phenomenon involves the incorporation of water molecules into certain weakly hydrated minerals, causing them to swell and promoting rock disintegration.

Examples include chloritization and the transformation of ferromagnesian minerals like pyroxenes and amphiboles into serpentine, chlorite, and epidote.

- Plagioclase + Pyroxene + Water -----> Amphibole (Green Hornblende)
- Plagioclase + Hornblende + Water -----> Chlorite + Actinote

4.1.2.2.3. Oxidation-reduction

These processes influence the migration and concretion of iron oxides, as ferrous iron (Fe²⁺), in its reduced state, is soluble, whereas in its oxidized state (Fe³⁺), it precipitates.

Oxidation primarily affects iron, which shifts from ferrous to ferric state. Example for olivine mineral:



Reductions are less common and occur in hydromorphic environments (permanently or periodically saturated with water), producing ferric iron as soluble ferrous iron.

Iron and dissolved oxygen in water react in the presence of bicarbonate to produce hematite and carbonic acid:



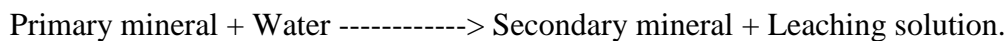
4.1.2.2.4. Hydrolysis (acidic or alkaline)

This process solubilizes minerals from the parent rock into ions.

It represents a form of chemical weathering where part of a mineral dissolves, while the remainder transforms into a new solid material, such as a clay mineral.

This alteration can be total, decomposing the mineral into its smallest components (hydroxides, ions), or partial, where degradation is incomplete and directly produces clay compounds.

The overall balance of a hydrolysis reaction can be expressed as follows:

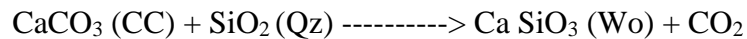


4.1.2.2.5. Decarbonation and carbonation

Are processes where carbon dioxide is respectively released or added.

Decarbonation involves the breakdown of carbonate minerals like calcite and dolomite.

An example is the decarbonation reaction of calcite (CC) in the presence of quartz (Qz), forming wollastonite (Wo):



4.1.2.3. Migration Phenomena (Descending and Ascending)

Climate is responsible for both ascending and descending migration phenomena, leading to the formation of accumulation horizons.

Additionally, other climatic elements such as wind, air humidity, and light play indirect roles by influencing vegetation.

4.1.3. Time

Time plays an essential yet often neglected role in soil differentiation across three distinct modalities.

Firstly, certain soil characteristics such as temperature, CO₂ concentration in the soil atmosphere, and the activity of living organisms evolve over time.

Secondly, other properties like water content, nitric nitrogen concentration, and pH vary seasonally, although these parameters tend to return to similar values each year.

Finally, over a multi-year scale, soils undergo phases of youth, maturity, and aging, demonstrating long-term evolution in their characteristics.

For example, from a soil already highly acidified, the process of neo-podzolization can manifest clearly over a depth of fifteen centimeters in just one hundred years.

4.1.4. Topography

Topography plays a significant role in the formation and modification of soil, acting as one of the primary factors influencing various soil properties such as texture, structure, and nutrient content. It interacts with other formation factors like climate, vegetation, and parent material, primarily affecting **erosion** and **leaching** processes.

4.1.4.1. Impact of Relief on Soil Formation

The **relief**, or the surface configuration of the land, is a key determinant of soil characteristics. It can significantly alter the nature of the soil by acting as an agent that truncates or removes the superficial horizons. In extreme cases, this can lead to the complete disappearance of soil layers. Relief influences the erosion and leaching processes, with slopes and altitude having specific effects on soil formation. **Erosion** is a key process in topography's interaction with soil. It can be categorized into two main types:

4.1.4.1.1. Accelerated Erosion

This occurs when climatic factors such as **rain**, **wind**, or **runoff** exert intense mechanical pressure on rocks and soils, causing rapid soil loss.

This is often exacerbated by human activities, such as deforestation or poor agricultural practices, which increase the vulnerability of soil to erosion.

4.1.4.1.2. Geological Erosion

Unlike accelerated erosion, geological erosion is a slower process where soil wear is gradually compensated by the slow formation of new rock layers or by the deposition of sediment.

This process is more common in regions where dense vegetation is present, helping to stabilize the soil and mitigate rapid erosion.

However, geological erosion can still lead to significant changes in the landscape over long periods.

4.1.4.2. Erosion and Leaching Dynamics

Topography also affects the **distribution of soluble and suspended elements** in the soil, mainly through processes like **leaching** and **infiltration**.

Leaching refers to the process by which water, typically rainfall or runoff, moves through the soil, carrying away soluble minerals and nutrients.

This can result in the leaching of **nutrients** from the upper soil layers, which can impact soil fertility.

On sloped terrain, water often flows more rapidly, which enhances the leaching process.

There are two primary phases associated with the movement of materials in the soil:

Migratory Phase

Soluble or suspended elements from the parent rock are transported deeper into the soil profile by infiltration waters.

This process can result in the downward movement of minerals, which may accumulate at greater depths.

Residual Phase

In this phase, water moving upwards through the soil, typically due to capillary rise or evaporation, brings minerals to the surface.

These elements, which may include salts or other soluble substances, accumulate near the soil surface, contributing to the **mineral skeleton** of the soil.

4.1.4.3.Slope, Altitude, and Water Distribution

The **slope** of the land plays a significant role in how water is distributed throughout the soil profile.

In areas with steep slopes, water tends to run off more quickly, reducing the amount of water that infiltrates the soil.

This runoff can carry away topsoil, leading to erosion and sediment deposition in lower-lying areas.

On flatter terrain, water infiltration is more gradual, allowing for deeper penetration and better nutrient retention.

Leaching on Slopes:

On inclined terrain, water tends to flow obliquely across the surface, carrying soluble or pseudo-soluble substances through aggregate filters. The movement of water on slopes accelerates the downward movement of minerals, which can affect the fertility and chemical composition of the soil.

High Altitudes and Organic Matter :

In **high-altitude areas** or on steep slopes, runoff is intensified, leading to water concentration in depressions and low-lying areas.

This encourages the accumulation of organic matter, which is vital for soil fertility.

At high altitudes, where water concentration is high, anaerobic conditions can also develop, especially in depressions where oxygen is limited. These conditions are conducive to the preservation of organic material, forming rich, fertile soils over time.

Low Altitudes and Runoff:

In **lower altitudes**, soils are often impacted by runoff from higher elevations, which can introduce additional nutrients and minerals.

The runoff contributes to the accumulation of organic matter, enhancing soil fertility.

However, in these areas, the water flow may also increase the potential for waterlogging and anaerobic conditions, especially in areas with poor drainage.

These conditions may favor the buildup of organic matter, further enriching the soil.

4.1.4.4. Topographic Influence on Erosion and Deposition Zones

In addition to leaching, the topography influences the overall erosion and sediment deposition dynamics.

For instance, **depressions and valleys** tend to act as natural sediment traps, where water slows down, allowing for the deposition of eroded material from higher elevations. These areas often become fertile zones where soil has built up over time, supporting rich vegetation. Conversely, **elevated areas** and **steep slopes** are more prone to erosion due to their greater exposure to wind and water forces.

The balance between erosion and deposition across different parts of the landscape leads to the creation of various soil types with different characteristics, depending on their position relative to the topography.

4.1.5. Biological Factors

Biological factors profoundly influence soil formation and its ongoing evolution, contributing to the dynamic interplay of physical, chemical, and biological processes that shape soil characteristics over time.

These factors include the roles of animals, plants, microorganisms, and lower organisms like mosses and lichens.

4.1.5.1. Animals

Soil fauna, ranging from microfauna to macrofauna, play essential roles in the soil-forming process.

Earthworms, termites, and ants contribute by bioturbation, which involves mixing and transporting soil particles and organic matter from deeper horizons to the surface.

These activities improve soil structure and aeration, enhancing water infiltration and nutrient cycling.

For example, springtails digest organic debris, converting it into humus, which is vital for soil fertility.

Larger animals, through their excretions and decomposition of carcasses, introduce organic matter and distribute fertilizing elements that enrich soil nutrient content.

Their movements also aid in breaking down compacted soil layers, promoting better aeration and root penetration.

4.1.5.2. Plants

Plants significantly influence soil development and transformation through their root systems and aboveground activities.

Roots penetrate deeply into the rock substrate, widening cracks and promoting weathering through the application of osmotic forces.

This process mobilizes and concentrates essential cations like potassium, calcium, and magnesium.

In the rhizosphere, root respiration alters the chemical environment by lowering pH and increasing CO₂ levels, encouraging microbial activity.

Microorganisms in this zone aid in decomposing organic matter and recycling nutrients, contributing to soil fertility.

Aboveground, plant litter leaves, stems, and other organic residues forms a protective layer that buffers the soil from erosion, temperature fluctuations, and atmospheric variations.

This organic matter decomposes into humus, enriching the soil with nutrients and improving its capacity to retain water.

4.1.5.3. Microorganisms

Microorganisms, including bacteria, fungi, and actinomycetes, are pivotal in driving the biogeochemical cycles of carbon, nitrogen, and other essential elements.

They decompose organic matter into simpler compounds, making nutrients available for plant uptake.

For instance, nitrogen-fixing bacteria transform atmospheric nitrogen into ammonia, an essential nutrient for plants.

Mycorrhizal fungi enhance nutrient absorption by extending root systems, particularly for phosphorus uptake.

Microbial activity also facilitates the breakdown of minerals and reactivation of inert elements into bioavailable forms, ensuring the continuous cycling of nutrients.

These processes are critical for maintaining soil fertility, promoting plant growth, and sustaining the broader terrestrial ecosystem.

4.1.5.4. Mosses and Lichens

Mosses and lichens are primary colonizers of bare rock surfaces and play a crucial role in initiating soil formation.

Lichens produce organic acids that chemically weather rock constituents, breaking them down into finer particles.

This process leads to the accumulation of organic and mineral residues, forming the foundation of soil.

Mosses trap moisture and organic debris, creating a microenvironment conducive to the establishment of higher plants and soil microbial communities.

Together, mosses and lichens facilitate the gradual transformation of rock into soil by contributing organic material and promoting the breakdown of mineral substrates.

4.1.5.5. Humans

Human activities exert a profound and multifaceted influence on soil formation, structure, and functionality.

While some interventions can enhance soil productivity and health, others may lead to degradation and long-term detrimental impacts.

The extent of human influence is evident in both rural and urban environments, where soils are subjected to intentional modifications or unintended consequences of human actions.

4.1.5.5.1. Extraction and Accumulation

Humans have long extracted natural resources such as minerals, clay, sand, and gravel for construction, manufacturing, and energy production.

These activities alter soil profiles by removing or redistributing material, often resulting in disrupted natural soil horizons.

Accumulation of residues, such as waste materials or construction debris around human settlements, introduces contaminants and affects the physical and chemical properties of the soil.

Urbanization compacts soil, reducing porosity and water infiltration while increasing surface runoff.

4.1.5.5.2. Agricultural Practices

Agriculture significantly reshapes soils through activities like plowing, tillage, and crop cultivation.

These practices modify soil structure, aeration, and nutrient dynamics, impacting its fertility. The partitioning of land into fields or terraces affects topography, erosion, and water retention.

Intensive agricultural systems, including monocultures, selective grazing, and meadow seeding, may lead to soil depletion, reduced biodiversity, and vulnerability to erosion. Conversely, sustainable practices such as crop rotation and conservation tillage can enhance soil health and resilience.

4.1.5.5.3. Chemical Interventions

Humans actively alter soil chemistry through the application of fertilizers, organic amendments, and lime.

These inputs replenish essential nutrients, improve fertility, and correct pH imbalances, promoting plant growth.

However, excessive or poorly managed applications can result in nutrient leaching, contamination of groundwater, and disruption of natural microbial communities.

Pesticides and herbicides further influence the biological balance of soil, potentially harming beneficial organisms and reducing biodiversity.

4.1.5.5.4. Water Management

Hydraulic interventions, such as irrigation, drainage, and sanitation, drastically transform soil water regimes.

Irrigation enables agriculture in arid regions but can lead to salinization if not properly managed.

Drainage systems, designed to remove excess water, alter natural water flow, potentially lowering water tables and affecting soil hydrology.

Conversely, poor drainage in certain areas may create waterlogged conditions, reducing soil aeration and organic matter decomposition.

4.1.5.5.5. Mechanical Alterations

Mechanical actions, including plowing, leveling, and earthmoving, have a direct impact on soil structure and composition.

Plowing aerates the soil, promoting microbial activity and decomposition of organic matter, but excessive plowing can lead to compaction and erosion.

Construction activities, such as the creation of terraces or roads, disrupt soil profiles and alter natural drainage patterns.

Quarrying and mining operations result in large-scale removal of soil and bedrock, often leaving behind degraded or contaminated landscapes.

4.1.5.5.6. Anthropization of Land

Approximately 40 to 50% of Earth's land surface is affected by anthropization, which includes both intentional transformations and unintended degradations.

Urban expansion, industrial activities, and land-use changes have led to significant modifications in soil properties and ecosystem dynamics.

Planting of single-species forests or the replacement of native vegetation with agricultural crops reduces soil biodiversity and can exacerbate erosion.

On the other hand, restoration projects, such as reforestation or soil remediation, aim to reverse these impacts, enhancing soil health and ecosystem services.

5. Soil Composition

5.1. Solid Fraction

5.1.1. Primary Minerals

The solid fraction of soils is mainly composed of primary minerals, dominated by silicates and aluminosilicates, accounting for nearly 99% of the mass and volume of the Earth's crust.

These silicates, with their fundamental unit in silica tetrahedrons (SiO_4), divide into various types based on their crystalline structure and alterability.

The most resistant minerals include quartz, muscovite, feldspars, and Phyllosilicates

Feldspars, found in most igneous and metamorphic rocks, vary in their resistance to weathering depending on their silica content, releasing essential plant nutrients.

Phyllosilicates, occur in layers and transform into vermiculites through weathering, thus influencing soil composition and structure.

while **ferromagnesian minerals** like **olivine, pyroxenes, and amphiboles** are more easily weathered, releasing iron, magnesium, and calcium.

5.1.2. Secondary Minerals

The secondary minerals of the soil, formed during pedogenesis through the alteration of primary minerals, typically constitute 95 to 99% of its composition.

They exhibit stability under various conditions such as hydration, oxidation, or soil reduction.

The nature of these minerals varies significantly in terms of particle size.

Secondary minerals include **clays, sands, silts, oxides (such as iron oxide, hematite), secondary carbonates (like calcite), aluminum (gibbsite), or manganese and crystallized iron (oxyhydroxides).**

5.1.2.1. Clays

Clays are formed by a group of clay minerals (**Phyllosilicates**) such as **illite, smectite, vermiculite, kaolinite, chlorite, glauconite**, as well as fibrous clays, associated with other minerals like **feldspars and quartz**, and containing impurities such as iron and titanium oxides.

This mixture exhibits characteristic plasticity and grain sizes smaller than $2 \mu\text{m}$, often poorly crystallized, resulting from the alteration of primary silicate rocks by hydrolysis.

Clay particles are distinguished by their beige color and electronegative charge.

Clay minerals are aluminum phyllosilicates, with layers composed of octahedral $\text{Al}(\text{OH})_6$ and tetrahedral SiO_4 layers linked by shared O and OH atoms.

The interlayer distance d separates successive layers, with frequent atom substitutions within the layers, which can disorder the crystalline structure and decrease its crystallinity.

Charge imbalances are compensated by cation adsorption in the interlayer space, contributing to the clay's exchange capacity.

Structurally, clays are primarily classified into 1/1 clays (one tetrahedral layer for one octahedral layer) and 2/1 clays (two tetrahedral layers for one octahedral layer).

5.1.2.2. Sands

Sandy elements result from the breakdown of rocks and can be predominantly siliceous, silicate-rich, or calcareous.

Sands are categorized into two mineral density fractions: heavy minerals (density greater than 2.9 g/cm^3) and light minerals (density less than 2.9 g/cm^3).

The particle diameter of sands ranges from 50 to 2000 micrometers, typically with a yellow color and neutral electrical charge.

5.1.2.3. Silts

Silts are composed of the same minerals as sands; however, their surface-to-volume ratio is higher, making them more susceptible to weathering, causing them to disappear relatively quickly.

In highly leached soils of ancient regions, the silt content is often very low.

Silts have a diameter ranging from $2 \mu\text{m}$ to $50 \mu\text{m}$, a dark color, and a neutral charge.

5.1.2.4. Secondary carbonates

These carbonates are primarily biologically derived, formed in aquatic environments such as freshwater or marine settings, and their dissolution in CO_2 -charged solution contributes to bicarbonate formation.

Calcium carbonates, such as **calcite** (CaCO_3) and **dolomite** ($\text{CaMg}(\text{CO}_3)_2$), are abundant in sedimentary rocks.

Calcite is the most common carbonate, while dolomite, containing both calcium and magnesium, is less prone to weathering under these conditions.

Other carbonates like **siderite** (FeCO_3) and **sodium carbonate** (Na_2CO_3) are also present, the latter only in alkaline halomorphic soils with a pH of 8.5 or higher.

5.1.2.5. Oxyhydroxides

These are constituents present in the fine fractions of the soil, primarily in clays, formed by the alteration of primary minerals, particularly **ferromagnesian minerals**.

They result from the combination of various metallic cations such as iron, aluminum, and manganese.

Iron oxyhydroxides are particularly represented by **goethite**, with an ochre color (FeOOH) in humid climates, and by red **hematite** (Fe_2O_3) in fersiallitic soils.

These minerals play an essential role in ensuring the bonds between clays and the organic matter of the soil.

In addition to iron, aluminum in ionic form plays a crucial role in binding organic matter to clays and can attach to vermiculite layers to form chlorites.

Crystalline forms of aluminum such as **gibbsite** ($\text{Al}(\text{OH})_3$) and **boehmite** (AlOOH) are rare in soils of temperate climates.

5.1.2.6. Sulfates and Chlorides

Sulfates and chlorides, common soluble salts in semi-arid or arid regions, include **halite** (NaCl) responsible for the white efflorescence of solonchaks (white saline soils), as well as **sodium sulfate** (Na_2SO_4) and **gypsum** ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).

Gypsum can accumulate significantly in arid soils, often beneath a layer of CaCO_3 accumulation.

These minerals, derived from saline rocks and influenced by local climate and hydrology, can significantly affect and differentiate soil properties.



Quartz



Muscovite



Feldspars



Illite



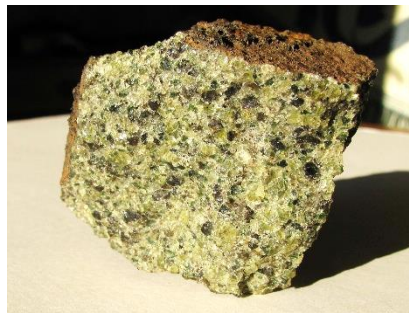
Smectite



Vermiculite



Kaolinite



Olivine



Glauconite



Chlorite

Figure 5. Primary Minerals (Original, 2025)



Clays



Sands



Silts



Calcite



Dolomite



Siderite



Sodium carbonate



Goethite



Hematite



Gibbsite



Boehmite



Halite



Sodium sulfate



Gypsum

Figure 6. Secondary minerals (Original, 2025).

5.1.3. Organic Constituents

A standard mineral soil typically contains between 2% and 5% organic matter, which is composed of carbon-based materials derived from the decomposition of plant and animal residues. This organic component plays an essential role in soil health and functionality.

It consists primarily of elements such as carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), along with secondary elements like sulfur (S), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg).

These elements form a complex matrix that interacts dynamically with the soil's mineral fraction, microorganisms, and environmental conditions.

Soil organic matter (OM) originates from the decomposition of plant litter, roots, and animal residues.

Saprophytic microorganisms, including bacteria, archaea, fungi, and soil fauna such as earthworms and springtails, break down these organic materials into simpler compounds.

This decomposition process is a cornerstone of the detritivore trophic network, cycling nutrients and energy through the soil ecosystem.

The final products of this breakdown, including humus, provide long-term stability to the soil's organic fraction.

Organic matter acts as a critical reservoir of nutrients for plants, holding essential elements like nitrogen, phosphorus, and sulfur in organic forms.

Through mineralization, these nutrients are converted into forms accessible to plants, ensuring sustained growth and productivity.

This reservoir function is particularly crucial in agricultural soils, where the replenishment of nutrients via organic amendments maintains fertility and crop yields.

One of the defining features of soil organic matter is its high cation exchange capacity (CEC), which allows it to adsorb and exchange positively charged ions (cations) such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}).

This property enhances the soil's ability to retain nutrients, reducing the risk of leaching, especially in sandy soils with low inherent fertility.

The interaction between organic matter and clays further amplifies this nutrient-retention capacity, creating a synergistic effect that supports plant nutrition.

Organic matter is vital for soil structure, contributing to the formation of stable aggregates. Polysaccharides and other organic compounds act as natural binding agents, linking mineral particles into aggregates.

These stable structures promote macroporosity, which is essential for root penetration, water infiltration, and gas exchange.

Additionally, well-aggregated soils exhibit enhanced resistance to water erosion, preserving the topsoil layer critical for plant growth.

Stabilized organic matter, particularly humus, significantly improves the soil's water retention capacity.

By forming the clay-humic complex, it helps soils hold moisture, making water available to plants during dry periods.

This property is particularly beneficial in arid and semi-arid regions where water availability is a limiting factor for agriculture.

Furthermore, organic matter aids in water filtration by trapping organic and mineral pollutants, contributing to groundwater quality and ecosystem health.

The dark color of organic matter absorbs sunlight, promoting soil warming in cooler climates. This warming effect accelerates microbial activity, particularly during early spring, when biological processes resume after winter dormancy.

Organic matter serves as an energy source for these microorganisms, fueling decomposition and nutrient cycling, which are essential for maintaining soil fertility and supporting plant growth.

Beyond its agronomic benefits, soil organic matter plays a pivotal role in environmental sustainability.

It sequesters carbon, mitigating greenhouse gas emissions, and supports biodiversity by providing a habitat and energy source for a wide range of soil organisms.

Its ability to filter and retain pollutants enhances soil and water quality, contributing to ecosystem resilience in the face of anthropogenic pressures.

5.1.3.1. Main Groups of the Organic Fraction

The organic fraction is divided into three main groups:

5.1.3.1.1. Living or Fresh Organic Matter

Originating from plant, animal, and microbial sources, this matter is present on the surface and in deeper soil layers, directly impacting soil properties.

These materials retain a composition similar to that of the living tissues they come from, including hydrocarbon substances like soluble sugars, starch, cellulose, lignin, and resin, as well as nitrogenous compounds primarily in the form of proteins, and mineral salts such as calcium, magnesium, and potassium.

5.1.3.1.2. Intermediate Organic Compounds

Intermediate organic compounds play a crucial role in the transformation of fresh organic matter, typically converted into simple mineral substances such as carbon dioxide, phosphates, and carbonates of calcium, magnesium, and sodium.

These transient products represent the young fraction of organic matter, also known as "young humus."

However, some of these products do not completely mineralize and halt their evolution. Instead of decomposing, their molecules condense, group, and polymerize to form new substances with very large molecules known as humic acids.

This process, called humification, constitutes the second stage of the organic matter evolution in soil. These compounds are transient and decompose easily.

5.1.3.1.3. Stabilized Organic Compounds

The main elements necessary for humus synthesis include oxidized residues of lignin and cellulose, nitrogenous matter such as proteins and amino acids, and mineral salts.

Humic acids, also known as stable humus, are produced during the humification process.

Brown humic acids are lightly colored, have medium molecular size, and are poorly condensed. They form stable clay-humic complexes with clay only with difficulty and flocculate slowly in the presence of high calcium concentrations.

Conversely, gray humic acids are very dark, have large, highly condensed molecules, and form very stable clay-humic complexes with clay, flocculating easily with low calcium concentrations.

Fulvic acids are imperfect humic products formed in very acidic and poorly aerated environments where microbial activity is significantly reduced, allowing for less effective fungal activity.

Fungi partially oxidize lignin, breaking it down into small molecules incapable of polymerizing. These substances are low in nitrogen, non-flocculable, unable to associate with clay, and generally soluble, making them prone to leaching.

However, they promote clay dispersion, and sometimes even its destruction, preparing it for migration to deeper layers, a phenomenon known as "podzolization."

Humine is a complex and heterogeneous product distinct from fresh organic matter.

Insoluble in extraction reagents, it is part of the bound organic matter.

It includes compounds resulting from the rapid evolution of organic matter, composed of barely transformed lignin in an active biological environment, such as in calcareous soils, as well as

highly polymerized compounds from a slow evolution associated with mineral matter, found in the Bh horizons of podzols.

5.1.3.2. Evolution of Organic Matter in Soil

The transformation of organic matter primarily occurs through two processes:

5.1.3.2.1. Humification and Peatification

Under anaerobic conditions, putrefaction or peatification occurs.

Some organic products, instead of fully mineralizing, halt their evolution. Their molecules group together, condense, and "polymerize" to form new large-molecule substances called humic acids.

An important characteristic of this process is the incorporation of nitrogen into humic macromolecules, leading to the storage of nitrogen in organic form in the soil.

Humification refers to the transformation of fresh organic matter into humic matter under normal ecological conditions, meaning with sufficient aeration and chemical richness. Humification occurs in several distinct phases.

The first phase, physical leaching, involves the solubilization of undecomposed organic debris (FOM) by rainwater, depriving these debris of easily mobilizable compounds such as sugars, mineral salts (Na, K, etc.), amino acids, and soluble phenolic compounds.

Next, the phase of physical disintegration occurs mainly through the action of soil fauna, fragmenting and pulverizing the organic debris, significantly increasing the surface area for microbial attack.

The third phase, biodegradation or bioreduction, is primarily microbial, involving the action of digestive enzymes from animals, including cellulolytic, hemicellulolytic, proteolytic, and lignolytic enzymes.

The following phase, proper humification, involves the formation of humic compounds (fulvic acids, humic acids, and humin) through chemical synthesis and condensation (polymerization), primarily by bacterial activity.

Finally, during the complexation phase, humic substances come into contact with mineral colloids, forming organo-mineral complexes.

These complexes, facilitated by earthworms, act as colloidal cement for the cohesion of soil aggregates.

In acidic environments, chelation complexes form, responsible for the deep migration of clay colloids and sesquioxides.

5.1.3.2.2. Mineralization

Mineralization represents the final phase of the transformation of organic substances, resulting in the release of mineral products into the atmosphere and soil, such as water, carbon dioxide, nitric acid, ammonia, and soluble mineral salts (K^+ , etc.).

5.1.3.2.2.1. Primary Mineralization

Primary mineralization is a relatively rapid process. It facilitates the release of nutrients through the sequential disintegration and depolymerization of organic matter.

These substances include water, CO_2 , nitric acid, phosphates, sulfates, etc.

This stage is mainly influenced by soil fauna, particularly fungi and bacteria.

The mineral matter thus released can be assimilated by plants, adsorbed onto the clay-humic complex, lost through leaching, or taken up by some microbes for the synthesis of microbial humin.

5.1.3.2.2.2. Secondary Mineralization

Secondary mineralization, on the other hand, is a very slow process, occurring at a rate of 2 to 3% per year. It influences the humus, which evolves over several years and releases significant amounts of nutrients annually, making them available to plants.

5.1.4. Colloidal Complexes

The soil has the capacity to adsorb various substances such as humic substances, clay, and sesquioxides, among others.

These substances form what are known as colloidal adsorbent complexes, consisting of colloids with either negative or positive charges.

These adsorbent complexes can fix exchangeable ions on their surfaces, significantly influencing the chemical properties of the soil.

Although essential elements for plant nutrition, such as K^+ and Al^{3+} , are present in limited quantities, calcium ensures a stable bond between clay particles and humus.

Plants absorb necessary cations like K^+ , Ca^{++} , and Mg^{++} by exchanging H^+ ions taken from water.

The ions retained at the periphery of the complexes are in an exchangeable form, allowing continuous exchanges with the ions present in the soil solution.

This ion absorption process is reversible: ions can be desorbed from the complex into the solution and vice versa, depending on the plants' needs and soil conditions.

The retained elements are divided into two categories: acid-generating ions like H^+ and Al^{3+} and "basic" ions such as Ca^{2+} , Mg^{2+} , K^+ , and Na^+ .

Soil colloidal complexes have several distinctive characteristics.

First, they are characterized by their extremely small size, with a diameter of less than 2 micrometers, requiring the use of an electron microscope for observation, unlike a standard optical microscope.

Due to their small size, soil colloids have a considerable external surface area per unit mass. For example, the external surface area of 1 gram of colloidal clay is about 1000 times greater than that of 1 gram of coarse sand.

Certain silicate clays can have extensive internal surfaces between the sheets of their crystalline units, significantly increasing their total surface area, ranging from 10 m²/g for clays with only external surfaces to more than 800 m²/g for those with extensive internal surfaces.

In the top 15 cm of one hectare of clayey soil, the colloidal surface area can reach up to 700,000 km²/g.

Furthermore, soil colloids carry electrical charges on their external and internal surfaces, mainly negative, influencing the interactions between particles through attraction or repulsion.

For example, silicate clay micelles, which are tiny colloidal particles, attract and fix positively charged ions on their surfaces.

Numerous water molecules are also associated with soil colloidal particles, transported by adsorbed cations between the silicate clay plates.

In terms of cohesion, clay particles show a strong tendency to stick together in the presence of water, thanks to mutual attraction reinforced by intercalated water molecules.

Lastly, the adhesion of colloids refers to their ability to attach to the surface of other materials or bodies they come into contact with, illustrating their complex and dynamic interaction with the soil environment.

Soil colloids are mainly classified into two categories, distinguished by their bonds and the compounds they form.

On one hand, inorganic colloids include oxides, organic substances, and soil ions that can form chemical complexes, often soluble or pseudo-soluble, favoring their migration in the soil until the complex is destroyed and the element fixed in an insoluble form.

For example, iron, even in ferrous form, is not soluble under ordinary soil conditions but can migrate and precipitate as ferric iron through oxidation.

Fulvic acids from the soluble fraction of organic matter can form important complexes with ions such as Fe²⁺, Fe³⁺, Mn²⁺, and Mn⁴⁺, existing in the soil at specific pH levels like 6.5 for Fe²⁺, 5 for Al³⁺, and 2.5 for Fe³⁺.

On the other hand, the clay-humic complex is an association between organic compounds (humus) and the clay constituents of the soil's mineral fraction, acting as a binder between mineral and organic particles.

About 50 to 80% of this organic matter is adsorbed onto clays, providing basic and acidic ions that are transitory and eventually disappear from the soil.

Organo-metallic complexes involve the binding of humified organic compounds with metallic cations such as iron, aluminum, and trace elements, forming more or less stable associations through cation exchange or coordination phenomena.

Monovalent cations like Na^+ and K^+ easily bind to humic compounds through cation exchange, while polyvalent cations like Cu^{2+} , Zn^{2+} , Mn^{2+} , Co^{2+} , Fe^{2+} , and Al^{3+} can form more complex bonds with organic compounds through coordinations where oxygen anions surround the metallic cation.

5.2. The Fluid Fraction

5.2.1. The Gaseous Phase

The gaseous phase of the soil, often referred to as the soil atmosphere, varies in composition depending on moisture conditions and is found within the soil's cavities or pores. Soil air, a crucial source of oxygen, is essential for the life of soil fauna and flora.

The gases present in the soil come from external air, the life activities of organisms, and the decomposition of organic matter.

The main gases in the soil include nitrogen (gaseous nitrogen (N_2), nitrogen dioxide (NO), nitrous oxide (N_2O), ammonia (NH_3), carbon dioxide (CO_2), and oxygen (O_2).

In dry soils, the gas is generally air, while in moist soils, it is a mixture of air and water vapor. Well-aerated soils contain about 180 to 205 ml of oxygen per liter of air, but this content can drop to 100 ml or less in flooded soils and microenvironments around plant roots.

The carbon dioxide content typically ranges from 3 to 30 ml per liter of soil, potentially reaching 100 ml per liter of air at depth or near roots in water-saturated environments.

Additionally, soil air includes other gases such as methane (CH_4), hydrogen sulfide (H_2S), and occasionally volatile organic compounds, along with argon (Ar) and water vapor.

The composition of soil air mainly depends on the geological environment it is in contact with, as well as rain and surface waters. It contains a variety of dissolved substances, both organic and inorganic, ionized and non-ionized. Predominant anions in the soil air include NO_3^- , HCO_3^- , CO_3^- , PO_4^- , Cl^- , and SO_4^- , while dominant cations include Ca^{++} , Mg^{++} , K^+ , Na^+ , and NH_4^+ .

Soluble organic matter, gaseous solvents, pesticides, and liquid fertilizers may also be present.

5.2.2. The Liquid Phase

The liquid phase of the soil is subdivided into several categories.

Gravitational water occupies macroporosity and moves downward.

Capillary water moves vertically and ascends, and is divided into **absorbable capillary water**, which occupies microporosity from 0.2 to 8 μm and composes the soil solution usable by plants, **and non-absorbable capillary water**, which occupies very fine porosity less than 0.2 μm . **Hygroscopic water** forms a thin layer surrounding mineral and organic particles and is very strongly retained.

This liquid phase plays a crucial role in several processes.

It participates in soil formation through the chemical weathering of parent rocks via processes such as dissolution, hydration, redox reactions, and hydrolysis.

Additionally, it is involved in the formation of organic matter, the transport of essential nutrients to plants, and the maintenance of plant temperature.

The liquid phase is subject to various forces, including gravity, surface tension, osmosis, and root suction.

The liquid phase is characterized by four reference soil moisture values: at saturation, at field capacity, at the wilting point, and at the critical point.

Each of these values determines favorable or unfavorable conditions for plant growth depending on water availability.

5.2.2.1. Reference Values of Soil Moisture

5.2.2.1.1. Saturation Moisture (θ SAT)

Saturation moisture is the water content of the soil at field saturation conditions. In reality, the soil never reaches complete saturation as some air always remains trapped.

5.2.2.1.2. Field Capacity Moisture (θ FC)

Field capacity moisture is the water content of the soil after excess water has drained away and the downward flow has become negligible, usually occurring one to three days after rain or irrigation.

This represents the upper limit of usable water for plant roots.

5.2.2.1.3. Wilting Point Moisture (θ WP)

As the name suggests, wilting point moisture represents the soil water content below which water absorption by the roots is blocked, causing plants to wilt.

At this point, the soil water potential is higher than that of the water in the plant.

5.2.2.1.4. Critical Point Moisture (θ CP)

Critical point moisture is the soil water content at which plants begin to suffer from a lack of water, affecting their growth.

This water content is used in irrigation management and is sometimes referred to as the temporary wilting point.

It falls between one-third and two-thirds of the difference between the wilting point and field capacity.

5.2.2.2. Water Potential in the Soil

The total water potential, Ψ_t , represents the energy required to move a unit of water reversibly from its reference energy state to that in the considered soil volume.

At equilibrium, this potential is uniform throughout the space.

Any spatial variation in water potential causes spontaneous movement toward lower potentials.

The term "potential energy" or simply "potential" describes the energy state of water in the soil.

Water potential can be expressed in different units depending on the amount of water measured, such as mass, volume, or weight.

The unit of energy in the International System (SI) is the Joule (J).

The components of soil water potential include gravitational potential, which represents the energy needed to move water to a certain altitude in the soil, and pressure potential, measurable with a tensiometer, varying with the water pressure in the soil.

The matric potential, negative and expressed in g/cm^2 or hPa, reflects the attraction of water by soil surfaces, influenced by pore size.

Finally, osmotic potential and root suction complete the soil water potential, representing the contribution of solutes and root attraction, respectively.

In summary, the soil water potential Ψ_w is the sum of these components :

$$\Psi_w = \Psi_0 + \Psi_P + \Psi_g + \Psi_m + \Psi_r$$

where:

- Ψ_0 : osmotic potential,
- Ψ_P : pressure potential,
- Ψ_g : gravitational potential,
- Ψ_m : matric potential,
- Ψ_r : root suction.

5.2.2.3. States of Water in the Soil

5.2.2.3.1. Field Capacity

Field capacity refers to the amount of moisture retained in the soil after excess water has drained and downward movement has significantly slowed, usually within 2 to 3 days following rain or irrigation on uniformly structured and textured permeable soils.

After irrigation, all soil pores are filled with water.

During gravitational drainage, larger soil pores contain both air and water, while smaller pores remain water-filled.

At this stage, the soil is said to be at its field capacity.

This moisture condition favors optimal water and nutrient absorption by plants.

$$\text{Field Capacity} = (\text{Ph} - \text{Ps}) / \text{Ps} * 100$$

Where :

Ph = wet weight,

Ps = dry weight.

5.2.2.3.2. Wilting Point

The wilting point, also known as the permanent wilting point, represents the amount of water per unit weight or volume of soil, expressed as a percentage, so tightly held by the soil's matric potential that roots cannot absorb it, leading to plant wilting. The wilting point moisture is generally around 55%.

5.2.2.3.3. Available Water Holding Capacity (AWHC)

The soil plays a crucial role in the water balance due to its capacity to store water, known as available water holding capacity (AWHC), measured in millimeters (mm).

This capacity varies significantly among soil types and even within the same soil type.

AWHC corresponds to the amount of water stored in a soil volume between the moisture limits of field capacity (FC) and permanent wilting point (PWP), available to plants.

The extreme values range from 50 mm to 250 mm, meaning a soil can store between 500 and 2500 m³ of water per hectare. Soils with low AWHC (< 80 mm) are very sensitive to drought, whereas irrigation is rarely necessary on soils with high AWHC.

Many methods exist to quantify AWHC, but the one proposed by Rawls et al. (Drain, 1982) is simple and reliable.

$$\text{AWHC (mm)} = (231,6 * 200 * \text{Sa} * 140 * \text{Ar} + 1410 * \text{OM}) * \text{h}$$

where:

Ar: clay content (in percentage),

Sa: sand content (in percentage),

OM: organic matter content (in percentage),

h: horizon thickness (in meters).

5.2.2.3.4. Readily Available Water (RAW)

Readily available water (RAW) refers to the amount of soil water that plants can use without significant stress. It is proportional to the available water holding capacity (AWHC)

$$\text{RAW} = k \times \text{AWHC}$$

where k depends on root depth and climatic conditions. Generally, k is often estimated at about 2/3.

RAW is more significant in deeper soils, where roots extend deeply, and when winter precipitation has been abundant.

5.2.2.4. Water Movement in the Soil

Water will only move through soil if there are forces driving this movement.

5.2.2.4.1. Infiltration

Infiltration, or percolation, refers to the primarily vertical movement of water as it infiltrates deeper soil horizons.

Soils are typically classified as permeable or impermeable based on their capacity to facilitate or restrict this movement.

The permeability (k) of a soil is defined by the rate of water infiltration and is measured using Darcy's law:

$$Q = k.s. H/h$$

where:

Q is the flow rate,

S is the cross-sectional area of the soil column,

H is the height of the water column,

h is the height of the soil column.

5.2.2.4.2. Filtration or Drainage

Filtration, also known as drainage, represents the flow of water through a saturated soil, where water fills all pore spaces, primarily through macropores.

5.2.2.4.3. Diffusion

Capillary diffusion of water in the soil does not depend on gravity but on variations in moisture between different points in the soil.

This phenomenon is observed as capillary rise of water from a wetter area to a drier one: evaporation at the surface creates a demand for water, driving this diffusion.

Water moves through the soil in the form of films made up of interconnected water molecules. The quality of transfer depends on the cohesion and continuity of these water films.

The rate of diffusion decreases as soil water content increases; water films surrounding soil particles are thinner when the soil is dry.

5.2.2.5. Soil Water Balance

The study of soil water balance is of interest to various scientific and technical disciplines such as soil science, agronomy, water management, irrigation consultancy, thermal remote sensing, and global climate modeling.

This water balance represents the difference between the inputs and losses of water in the soil, allowing for quantification of exchanges between the atmosphere and the soil-vegetation system.

It is particularly crucial in agronomy as it evaluates variations in available soil water reserves for plants.

Depending on its texture and structure, the soil can store and release water to vegetation. These exchanges between the atmosphere, soil, and plants manifest as various fluxes.

Thus, the water balance synthesizes all these exchanges, including precipitation, surface and subsurface runoff, and evaporation.

5.2.2.5.1. Calculation of the Water Balance

The water balance equation is based on the principle of conservation and can be formulated as follows for a given period and geographic area:

$$P+S=R+E +(S+ \Delta S)$$

Where:

P : precipitation (liquid and solid) [mm],

S: resources (accumulation) from the previous period (groundwater, soil moisture, snow, ice) [mm],

R : surface runoff and subsurface flows [mm],

E : evaporation (including evapotranspiration) [mm],

S+ΔS : resources accumulated at the end of the period [mm],

ΔS: change in soil water storage.

5.2.2.5.2. Components of the Water Balance

When a plant is well-supplied with water, its water consumption, called ETM or maximum evapotranspiration, can be calculated from the climatic demand, which is the potential evapotranspiration.

5.2.2.5.2.1. Potential Evapotranspiration (ETP)

Potential evapotranspiration, or ETP, represents the combined water loss through two main processes:

- 1) transpiration from a well-watered vegetation cover and
- 2) evaporation from the soil surface.

These processes are influenced by factors such as temperature, humidity, sunlight, and wind. ETP values indicate the amount of water lost that needs to be replaced by irrigation and/or precipitation.

$$ETP = k \left(\frac{T}{T+15} \right) \cdot (R_g + 50) \text{ (mm/month)}$$

Where:

T : average monthly temperature,

R_g: global solar radiation,

k=0.37 for February, **k=0.40** for other months,

$$R_g = I_{ga} (0,18 + 0,62 h/H)$$

where

I_{ga} : direct solar radiation in the absence of atmosphere,

h/H: actual sunshine duration/maximum possible duration (varies between 1 and 0.1).

5.2.2.5.2.2. Maximum Evapotranspiration (ETM)

The maximum evapotranspiration of a crop is "the maximum amount of water it is likely to evaporate when placed under good water supply conditions and for a soil near field capacity." It depends on the soil cover by the crop and its physiological state.

The calculation of ETM involves crop coefficients that reflect the specific characteristics of each type of plant at a given development stage.

$$ETM = K_c \times ETP$$

The crop coefficient (K_c) adjusts the potential evapotranspiration (ETP) according to the specific crop type and its growth stage.

As the crop advances vegetatively, K_c tends towards 1, at which point ETP equals the maximum evapotranspiration (ETM).

K_c is determined according to the specificities of each crop and its growth cycle, with tables available to guide these calculations.

5.2.2.5.2.3. Actual Evapotranspiration (ETR)

Actual evapotranspiration corresponds to the amount of water (in mm) evaporated by the soil and transpired by the plant per day under normal cultural conditions.

Its calculation is complex as it depends on the available water stock at a given moment.

Therefore, the ETM, i.e., the maximum evapotranspiration, adjusted by a crop coefficient (K_c), is used to estimate the actual evapotranspiration under real conditions.

$$\text{ETR (mm/year)} = P / (0.9 + (P^2/L^2))^{0.5}$$

$$L = 0.05 T^3 + 25T + 300$$

Where:

- P : precipitation in mm,
- T : temperature in °C,

5.2.2.6. Plant Water Requirements

Water is the primary constituent of plants, accounting for more than 80% of their mass. This remarkable composition highlights the indispensable role of water in supporting plant survival, development, and growth.

As the medium for critical physiological processes, water ensures the efficient functioning of plants and their adaptation to environmental conditions.

Water facilitates the production of energy through photosynthesis, a fundamental biochemical process where plants convert solar energy into chemical energy stored as glucose.

In this process, water molecules are split to release oxygen and provide essential components for sugar synthesis.

In addition to energy production, water plays a crucial role in nutrient transportation. Absorbed through the roots, water carries dissolved minerals and nutrients upward through the plant's vascular system (xylem) to reach the leaves and other tissues.

This movement, coupled with the evaporation of water from the leaf surface (transpiration), helps regulate plant temperature, preventing heat stress and maintaining metabolic balance.

Water requirements in plants vary significantly across different stages of development:

- **Seeding Stage:**

During germination, water activates metabolic processes that initiate seed growth, including enzyme activity and cell division.

- **Planting and Repotting:**

Adequate watering minimizes transplant shock, ensuring that roots adapt to new soil conditions while maintaining hydration for initial growth.

- **Growth Phase:** As plants grow, their demand for water peaks due to increased cell division, leaf expansion, and photosynthetic activity.

This phase is critical for crops, as insufficient water can directly impact yields.

The amount of water a plant consumes is influenced by a combination of environmental and biological factors.

The primary components contributing to water consumption include:

- **Leaf Transpiration:**

The loss of water vapor through the stomata, influenced by light, temperature, and humidity.

- **Soil Evaporation:**

The direct evaporation of water from the soil surface, which reduces moisture available to plant roots.

Factors Affecting Water Consumption

The level of water consumption is shaped by several key factors:

- **Sunlight Duration:** Longer daylight hours increase photosynthesis and transpiration rates.
- **Temperature:** High temperatures accelerate evaporation and transpiration, raising water demands.
- **Air Humidity:** Low humidity increases the gradient for water vapor loss, intensifying transpiration.
- **Air Movement:** Wind promotes the removal of water vapor near leaf surfaces, enhancing transpiration.
- **Species and Variety:** Some species are more water-efficient due to adaptations like deep roots or waxy leaves.
- **Development Stage:** Water needs are higher during stages of active growth and reproduction.

Potential Evapotranspiration (ETP)

The combined effects of climatic factors on water consumption are captured by the concept of potential evapotranspiration (ETP).

This variable represents the theoretical amount of water lost through evaporation and transpiration under specific weather conditions, calculated using meteorological data such as temperature, sunlight, wind speed, and humidity.

ETP is a crucial parameter for determining irrigation requirements and water resource management in agriculture.

The "plant" criterion is accounted for by a coefficient called the crop coefficient (Kc), which varies according to the plant species and its development stage.

From these two variables, the daily water consumption for a plant can be deduced:

$$\text{Consumption (mm/day)} = \text{ETP (mm/day)} \times \text{Kc}$$

(Note: 1 mm = 1 liter/m²)

5.2.2.7. Method for Assessing the Amount of Available Water

To determine when and how much to water, it is necessary to perform a water balance, taking into account water inputs and losses at the "soil reservoir" level.

The amount of available water is calculated as follows:

$$\text{Available water quantity} \\ = \text{Stock} + \text{Inputs (rain + capillary rise + irrigation)} - \text{Outputs (consumption + runoff + drainage)}$$

5.2.3. Relationships Between the Three Phases of Soil

In natural soil, various elements such as air, water, and grains are distributed in a dispersed manner, forming a structure influenced by both environmental conditions and its historical evolution.

The volumes of solids, liquids, and gases are typically expressed in m³ or cm³.

The relationships between the different volumes are represented by the following equations :

$$V_t = V_s + V_v = V_s + V_w + V_a \\ V_v = V_w + V_a$$

Where :

V_t = total soil volume (cm³)

V_s = volume of solids (cm³)

V_v = volume of voids (cm³)

V_w = volume of water or liquid (cm³)

V_a = volume of air or gas (cm³)

5.3.1. Fauna

The soil fauna is divided into several categories based on their size and functions.

5.3.1.1. Microfauna

The **microfauna**, which measures **less than 0.2 mm**, includes **protozoa** that feed on bacteria, and **nematodes** that decompose plant and animal debris while feeding on bacteria, protozoa, and fungi.



Figure 7. Protozoa (example :*Paramecium aurelia*) (Original, 2025)

Nematodes, commonly known as roundworms, are one of the most abundant and diverse groups of multicellular organisms in terrestrial and aquatic ecosystems.

They play indispensable roles in soil functionality and ecological balance, contributing to nutrient cycling, organic matter decomposition, and soil food web dynamics.

Their diversity and ecological importance make them central to soil science and agricultural sustainability.

General Characteristics of Nematodes

Nematodes are unsegmented, cylindrical worms that exhibit a wide range of physical and ecological traits:

- **Appearance:**

Nematodes are often translucent or light-colored, sometimes even transparent, making them challenging to observe without magnification.

- **Diversity:**

To date, approximately 23,000 species have been described, but it is estimated that there could be up to one million species yet to be discovered.

- **Habitat:**

- These organisms thrive in diverse environments, including soils, freshwater, and marine systems, and adapt to a range of conditions from arid deserts to dense rainforests.

Functional Classification Based on Feeding Habits

Soil nematodes are categorized into five functional groups, each reflecting specific ecological roles :

Bacterivores :

- Feed on soil bacteria, regulating their populations and promoting nutrient cycling.
- Their abundance is often correlated with increased microbial activity, making them indicators of fertile and healthy soils.

Fungivores :

- Consume fungal hyphae and spores, contributing to the regulation of fungal populations.
- Their numbers may increase in stressed soils (e.g., acidification or contamination), signaling changes in soil decomposition pathways.

Herbivores :

- Feed on plant roots and tissues, often causing significant agricultural damage.
- Over 4,100 phytoparasitic species are known, including economically important pests such as root-knot nematodes (*Meloidogyne spp.*) and cyst nematodes (*Heterodera* and *Globodera spp.*), which impair water and nutrient uptake in plants.

Omnivores :

- Exhibit a versatile diet, feeding on bacteria, fungi, and smaller soil organisms.
- Play a dual role in nutrient cycling and soil food web interactions.

Predators :

- Prey on other nematodes and microfauna, helping control pest populations and maintaining ecological balance.

Free-Living Nematodes

- Free-living nematodes, which include bacterivores, fungivores, omnivores, and predators, represent 60–80% of the soil nematode community.

They perform critical ecological functions:

- **Nutrient Cycling:**

By consuming microbes, they facilitate organic matter decomposition and release nutrients into the soil, making them available for plant uptake.

- **Energy Transfer:**

As primary consumers, nematodes transfer energy through the soil food web, linking microbial populations to higher trophic levels.

- **Soil Structure Enhancement:**

Their activity promotes the breakdown of organic matter and contributes to the formation of soil aggregates, improving soil aeration and water retention.

Herbivorous Nematodes in Agriculture

Herbivorous nematodes, particularly phytoparasitic species, pose major challenges to agriculture:

- **Economic Impact:**

Root-knot nematodes and cyst nematodes are among the most damaging pests, causing root deformities, nutrient deficiencies, and yield losses.

- **Control Measures:**

Management strategies include crop rotation, use of resistant plant varieties, and biological control agents to mitigate their impact.

Indicators of Soil Health

Nematode populations are sensitive to changes in soil conditions, making them valuable bioindicators:

- **Population Dynamics:**

Increased bacterivore populations indicate high microbial activity, while stress conditions such as contamination or acidification may shift dominance to fungivores.

- **Environmental Monitoring:**

Studying nematode community composition provides insights into soil health, nutrient availability, and ecosystem stability.

Nematodes in Soil Ecosystem Functionality

The ecological roles of nematodes extend beyond their direct interactions with soil organisms:

- **Decomposition and Nutrient Recycling:**

By consuming bacteria and fungi, nematodes accelerate the decomposition of organic matter and the release of nutrients essential for plant growth.

- **Soil Food Web Dynamics:**

Nematodes act as keystone species, linking microbial decomposers to higher trophic levels and enhancing energy flow within ecosystems.

- **Soil Quality Indicators:**

Their sensitivity to environmental changes makes them reliable indicators for assessing soil health, contamination levels, and restoration success.



Figure 8. Nematodes (example : *Globodera spp.*) (Original, 2025)

5.3.1.2. The mesofauna

The mesofauna, measuring **from 0.2 mm to 2-4 mm**, includes **mites and springtails (*Collembola*)**.

Mites form a very heterogeneous group of arachnids whose regressive evolution has altered body segmentation.

They generally have six legs in the larval stage and eight legs in the nymphal and adult stages, with a size ranging from 0.1 to 1 mm.

Soil mites are chelicerate arthropods and often the most abundant microarthropods in various types of soil.

A 100 g soil sample can contain up to 500 mites.

Four suborders of mites are frequently found in soils: **Oribatei, Prostigmata, Mesostigmata, and Astigmata**.

Occasionally, mites from other habitats, such as spider mites (plant mites), predatory mites found on vegetation, and parasites of vertebrates or invertebrates, can also be found.

Oribatid mites (Oribatei) are typical of soils and are generally fungivores or detritivores.

Mesostigmatid mites are primarily predators of small fauna, although some species are fungivores and can become numerous.

The Prostigmata include a wide range of soil species, many of which are predators, while some families contain mites that feed on fungi.

The larger predatory prostigmata feed on arthropods or their eggs, while the smaller species are nematophagous.

Astigmatid mites, which lack stigmata and breathe through their cuticles, often lack eyes and are equipped with crushing chelicerae ending in a pincer.

Some soil mites fragment and facilitate the decomposition of plant debris, thus promoting humus formation, while others are carnivorous, shredding their prey with their chelicerae. Astigmatid mites are also significant pests of stored products, often associated with accumulations of residues in humid conditions.



Figure 9. Mites (example : European Red Mite *Panonychus ulmi*) (Original, 2025)

Springtails (Collembola) are a class of small, primitive arthropods, formerly considered apterygote insects but now classified among the hexapods.

They are divided into more than 3,000 species and measure an average of 2 mm.

These small, wingless arthropods have antennae and a segmented body.

They are categorized into four orders : *Entomobryomorpha*, *Poduromorpha*, *Symphyleona*, and *Neelipleona*.

Some species of springtails contribute to the fragmentation of dead plant material (leaves, needles, roots) and the mineralization of organic matter by consuming dead plant organs or the feces of other invertebrates.

Their activity plays a role in the superficial structuring of the soil, particularly the OF and OH horizons of humus.

Additionally, they participate in the dispersal of fungal spores, soil aeration, and the creation of soil micro-porosity.

Most soils contain approximately one million springtail feces per square meter, which significantly contributes to the return of essential nutrients for plants.

The most important impact of springtails lies in their consumption of fungal hyphae and bacteria, accounting for about 1% of the annual microbial population.



Figure 10. Springtails (example :*Folsomia quadrioculata*) (Original, 2025)

5.3.1.3. The macrofauna

The macrofauna, **exceeding 2-4 mm**, is represented by

5.3.1.3.1. Annelids

Earthworms which are responsible for the formation of clay-humic aggregates during their digestive transit.

Earthworms, members of the phylum **Annelida**, are characterized by their cylindrical and elongated bodies composed of segments called metameres, extending between a head lobe (prostomium) and a terminal lobe (pygidium).

They possess a closed circulatory system, sometimes with red blood, and their skin is kept moist and sticky by mucus.

Hermaphrodites, they do not have a respiratory system and perform gas exchanges directly through their skin.

Annelids are divided into three main classes:

Polychaetes, primarily marine with locomotive bristles on parapodia; **Achaeta or Hirudinea**, such as leeches, lacking bristles and attached by suckers; and **Oligochaetes**, including terrestrial or freshwater earthworms, characterized by a limited number of bristles directly implanted in their integument.

Earthworms, particularly members of the Lumbricidae family such as *Lumbricus* and *Eisenia*, play a crucial role in ecosystems by aerating and fertilizing the soil.

Their ability to absorb water and their preference for certain soil types, such as loamy and clay-sandy soils, influence their distribution and abundance.

Additionally, their cocoon-laying activity is closely related to temperature, with specific preferences for moderate temperature ranges, thus contributing to their ecological regulation in various habitats.

They bring clay and ions from the deeper layers of the soil to the surface, playing a crucial role in litter decomposition, soil aeration, and structuring the A horizon.

Moreover, they facilitate the formation of organo-mineral complexes.

Earthworms are also sensitive to variations in soil pH, with some species preferring acidic soils while others thrive in more alkaline environments.

Their biological activity and behavior, such as body temperature regulation and response to drought conditions, demonstrate their adaptability to environmental changes.

As efficient decomposers, they contribute to the breakdown of organic matter, thereby enhancing soil fertility and recycling essential nutrients for plants.

Their role in soil structure, particularly in improving porosity and facilitating the movement of water and nutrients, makes them key players in terrestrial ecosystems.



Figure 11. Earthworms (example :*Eisenia fetida*) (Original, 2025)

Enchytraeids play a crucial role in the decomposition of poorly decomposed plant debris, thus contributing to the formation of the OH horizon through their droppings.

Their life cycle is relatively short, about 50 days.

They are considered indicators of chemical stress in terrestrial ecosystems and, more recently, as indicators of agricultural practices in agroecosystems.

They are heavily involved in the degradation of soil organic matter, ingesting large amounts of organic matter (more than 2 kg of mineral soil per square meter annually in agricultural plots). Their burrowing behavior and the production of fecal pellets contribute to the evolution of soil structure, influencing porosity, reducing compaction, and increasing hydraulic conductivity as well as oxygen concentration.

Additionally, enchytraeids participate in the transport, ingestion, and mixing of mineral and organic soil particles. More recently, a study showed that their presence could influence the development of phytopathogenic fungi.



Figure 12. Enchytraeids (example :*Achaeta spp*) (Original, 2025)

5.3.1.3.2. Arthropods

Arthropods feed on bacteria, algae, animal droppings, and fungi, finely fragmenting soil particles to increase the surface area for fungal and bacterial attack.

5.3.1.3.2.1. Isopods

Woodlice, often referred to as "terrestrial isopods," are actually crustaceans fully adapted to terrestrial life.

Among them, the common woodlouse (*Armadillidium vulgare*) is widely distributed, measuring from 0.5 to 2 cm depending on the species and capable of rolling into a ball when threatened.

Their bodies are segmented and flattened dorsoventrally, consisting of three distinct parts: the head, thorax, and abdomen, protected by a rigid, articulated exoskeleton.

Woodlice come in various shades ranging from yellowish to black, with some having an almost transparent carapace.

These crustaceans play a crucial role in the decomposition of leaf litter, significantly contributing to nutrient cycling and ecosystem services in the soil.

They are also used as models in soil ecotoxicology for laboratory tests, monitoring studies, and bioindication in the field due to their sensitivity to environmental changes.

Woodlice have high moisture requirements, losing water rapidly through evaporation via their cuticle, which leads them to primarily inhabit moist and dark environments, such as under rocks or in damp forest areas.

Primarily nocturnal, they feed mainly on decaying plant matter, acting as important detritivores in ecosystems.

Additionally, their presence in various habitats can provide valuable insights into soil health and biodiversity.



Figure 13. Woodlice (example :*Armadillidium vulgare*) (Original, 2025)

5.3.1.3.2 Spiders (Araneae)

Spiders (Araneae) belong to the class Arachnida, which also includes scorpions, ticks, and mites.

Araneae is the largest order of arachnids, with 113 families, 4,033 genera, and 46,499 species described to date.

Spiders are distinguished from other arachnids by their ability to produce silk from the end of their abdomen and by their prosomal venom glands, which release venom through their chelicerae modified into fangs.

Their colors mainly range between browns and blacks, although many species are colorful.

Unlike other arachnids, the abdomen of spiders shows no trace of ancestral segmentation.

The smallest spiders belong to the family Symphytognathidae, measuring less than 1 mm long as adults.

Spiders can be defined as air-breathing arthropods with two body parts : the cephalothorax and the abdomen.

Unlike insects, spiders have four pairs of legs attached to the cephalothorax, each composed of seven segments : coxa, trochanter, femur, patella, tibia, metatarsus, and tarsus.

They also have fang-shaped chelicerae that inject venom.

Most spiders have eight simple eyes, although some species have more or fewer.

Spiders significantly influence the structure and function of ecological communities through their direct and indirect effects on herbivores and omnivores.



Figure 14. Spiders (example : *Cyrba algerina*) (Original, 2025)

5.3.1.2.2.3. Myriapods

Myriapods, on the other hand, constitute a distinct phylum of terrestrial arthropods characterized by an elongated, segmented body with numerous pairs of legs.

Comprising four main classes (*Chilopoda*, *Diplopoda*, *Symphyla*, and *Pauropoda*), this group includes about 13,000 known species to date, widely distributed across the globe.

The Chilopoda and Diplopoda are the most significant classes, with approximately 3,000 and 10,000 species, respectively.

Centipedes, members of the Chilopoda class, are primarily carnivorous, equipped with venomous claws, whereas other classes, such as the Diplopoda, are mainly detritivores, contributing substantially to litter decomposition and nutrient recycling in terrestrial ecosystems.

Recent studies in molecular phylogenetics indicate that myriapods form a monophyletic group closely related to pancrustaceans such as crustaceans and insects, and they were among the first animals to colonize terrestrial habitats.

Myriapods, through their adaptation to a diversity of terrestrial habitats, play a crucial role in ecosystems by contributing to the decomposition of organic matter and nutrient recycling.

Their global distribution reflects their ability to adapt to a variety of environmental conditions, from humid tropical forests to arid deserts.

Centipedes, like the members of the Chilopoda class, are distinguished by their venomous claws and carnivorous diet, making them effective predators of other invertebrates.

In contrast, millipedes, with their predominant role as detritivores, actively participate in transforming dead plant material into humus, thus promoting soil fertility.

Myriapods, as an ancient group among terrestrial arthropods, have evolved to occupy various ecological niches, thereby contributing to the diversity and stability of terrestrial ecosystems worldwide.



Figure 15. Myriapods (example : *Scolopendra cingulata*) (Original, 2025)

5.3.1.3.2.4. Dipterans

Adult dipterans are insects with a single pair of wings, the second pair having evolved into small halteres, which allow the fly to maintain its balance in flight.

Their larvae are wingless, legless, and their appearance varies significantly between species. Their size can range from 2 to 40 mm.

Most larvae are phytophagous, phytosaprophagous, coprophagous, or necrophagous, and they effectively contribute to the fragmentation of litter.



Figure 16. Dipterans (example : *Musca domestica*) (Original, 2025)

5.3.1.3.2.5. Coleopterans

Adult beetles have a pair of tough wings called elytra, which protect the membranous wings used for flight.

Many beetle families are adapted to life in soil and litter. Their larvae, as well as adults, are often saprophagous and coprophagous, but they can also feed on living roots (rhizophages) and fungi (mycophages).

Some species are also predatory. Beetles play a crucial role as decomposers, although rhizophagous species can cause significant damage to crops, such as larvae of beetles, wireworms, and weevils.



Figure 17. Beetles (example : *Coccinella septempunctata*) (Original, 2025)

5.3.1.3.2.6. Thysanurans

Silverfish, or thysanurans, are insects with shuttle-shaped bodies, featuring two cerci and an epiproct covered in bristles at the tip of the abdomen.

Their bodies are covered with scales.

As detritivores, they feed on various debris and often live under stones alongside ants, but they are also found in human dwellings.



Figure 18. Thysanurans (example : *Lepisma saccharina*) (Original, 2025)

5.3.1.3.2.7. Dermapterans

Earwigs, belonging to the order Dermaptera, are insects with elongated, flattened bodies and distinctive abdominal pincers, or forceps, which are more prominent in males.

These forceps serve various purposes, including defense, prey capture, and assisting in folding their hind wings. Some species are entirely wingless, while others possess vestigial or fully developed wings, though flight is rare.

Their complex mouthparts are adapted for chewing and are particularly striking when observed under magnification, showcasing their intricate design.

Earwigs are predominantly nocturnal and play an essential role in ecosystems as decomposers and occasional predators.

They feed on a variety of organic materials, including decaying plant matter, fungi, and small invertebrates, contributing to the recycling of nutrients within the soil.

Some species also act as biological control agents by preying on pests such as aphids and mites, offering potential benefits in agricultural systems.

Despite their beneficial roles, earwigs are often misunderstood due to myths surrounding their behavior.

Their presence in gardens and natural habitats is generally harmless, and they contribute to the overall balance of ecosystems by participating in the breakdown of organic matter and maintaining pest populations.



Figure 19. Dermapterans (example :*Forficula auricularia*) (Original, 2025)

5.3.1.3.2.8. Neuropterans

The insect order Neuroptera, often referred to as net-winged insects, includes diverse species such as lacewings, mantisflies, antlions, and their relatives.

With approximately 6,000 described species worldwide, Neuroptera exhibits a remarkable range of ecological roles and morphological adaptations.

This order is grouped with Megaloptera (e.g., alderflies, fishflies, and dobsonflies) and Raphidioptera (snakeflies) within the broader taxonomic clade Neuropterida, formerly known as Planipennia.

Adult neuropterans are distinguished by their four membranous wings, which are roughly equal in size and elaborately veined, giving them a delicate, net-like appearance.

Their wings are highly functional for flight, aiding them in navigating diverse habitats. Neuropterans also possess chewing mouthparts, which are well-adapted for their feeding habits, and undergo complete metamorphosis, progressing through egg, larval, pupal, and adult stages. The larvae of many neuropterans are highly specialized predators, with some species, like green lacewings (*Chrysopidae*), playing a critical role in controlling pest populations such as aphids, mites, and whiteflies in agricultural and natural ecosystems.

Antlion larvae, often referred to as "doodlebugs," are well-known for their pit-trapping behavior, where they ambush prey such as ants.

Mantisflies, with their mantis-like forelegs, are also adept predators, often feeding on spiders and other small arthropods.

Neuropterans contribute to ecological balance by regulating pest populations and recycling organic matter.

Despite their fragile appearance, these insects are resilient and occupy a variety of habitats, ranging from forests and grasslands to arid regions.

Their diversity, predatory nature, and ecological significance make them a fascinating and important group within the insect world.



Figure 20. Neuropterans (Example : *Chrysopa* sp) (Original, 2025)

5.3.1.3.2.9. Isopterans

Termites, belonging to the order Isoptera, are eusocial insects known for their complex colony organization and division of labor based on castes.

Each caste fulfills specialized roles to ensure the colony's survival. The reproductive castes, consisting of kings and queens, are responsible for reproduction and colony expansion. Queens are particularly notable for their remarkable size and longevity, often laying thousands of eggs daily.

Soldiers, equipped with specialized jaws or chemical defense mechanisms, protect the colony from predators, while workers manage essential tasks such as foraging, nest construction, and caring for eggs and larvae.

Globally, there are approximately 2,750 described termite species, most of which are found in tropical and subtropical regions.

Termites are particularly abundant in humid tropical forests, where they serve as primary decomposers of cellulose, breaking down wood, leaf litter, and other plant material. This decomposition process recycles nutrients, enriches the soil, and enhances its structure, contributing to ecosystem productivity.

In addition to their role as decomposers, termites create intricate networks of galleries and mounds that improve soil aeration and water infiltration, further supporting plant growth.

Termites are also critical to ecosystem resilience, particularly in drought-prone areas. Their activity helps maintain soil moisture levels and promotes the decomposition of organic matter even under challenging conditions, ensuring that nutrients remain available for other organisms. Furthermore, their symbiotic relationships with gut microorganisms, such as protozoa and bacteria, allow them to efficiently digest cellulose, making them unique contributors to carbon cycling and energy flow in ecosystems.

While termites are essential for natural ecosystems, some species are considered pests due to their ability to damage wooden structures and crops. Despite this, their ecological importance far outweighs their occasional negative impacts. Understanding their roles in nutrient cycling, soil health, and ecosystem stability underscores the significance of termites as key players in maintaining biodiversity and supporting life on Earth.



Figure 21. Termites (Example :*Lafleur Termites*) (Original, 2025)

5.3.1.3.2.10. Hymenopterans

Ants, social insects of the family Formicidae, vary in size from 2 to 25 mm and in color from yellow to black. Typically, an ant has a large head and a slender, oval abdomen connected to the thorax by a narrow waist.

Ant colonies generally consist of three castes : queens, males, and workers.

Some species live as parasites in the nests of others.

Ants build nests in the ground, under rocks, or above ground with twigs, sand, or gravel.

Their life cycle, including egg, larva, pupa, and adult stages, lasts from 8 to 10 weeks.

The queen lays eggs throughout her life, while the workers, all females, carry out colony tasks.

Larger individuals, called soldiers, defend the colony.

These diverse insects play important ecological roles, including in the decomposition of organic matter, soil aeration, and regulation of populations of other organisms.



Figure 22. Ants (Example :*Formica fusca*) (Original, 2025)

5.3.1.3.3.Mollusks

Mollusks play a significant role in the decomposition of cellulose and the mixing of organic matter within ecosystems. By feeding on plant debris, they help break down complex carbohydrates like cellulose, facilitating their conversion into simpler compounds that can be utilized by microorganisms.

This activity contributes to nutrient cycling and improves soil structure by incorporating organic matter into the soil. Furthermore, mollusks aid in aerating the soil through their movement and burrowing behaviors, promoting better oxygen diffusion and microbial activity.

Their contribution is essential to maintaining soil health and supporting ecosystem productivity.



Figure 23. Snails (Example : *Helix pomatia*) (Original, 2025)

5.3.1.4. Megafauna

Megafauna mammals, such as moles and voles, play a crucial mechanical role in soil ecosystems. Through their burrowing and digging activities, they contribute to soil aeration, which enhances gas exchange and facilitates root penetration for plants.

This mechanical action also aids in breaking up compacted soil layers, improving water infiltration and reducing surface runoff.

Additionally, their movement redistributes organic material and nutrients throughout different soil layers, promoting a more homogeneous nutrient profile.

These animals indirectly support microbial activity by creating habitats for microorganisms and increasing the surface area available for microbial colonization.

Their role in shaping the physical and biological properties of soil makes them indispensable to maintaining healthy ecosystems.



Figure 24. Wood mice (Example : *Apodemus sylvaticus*) (Original, 2025)



Figure 25. Moles (Example : *Talpa aquitania*) (Original, 2025)

5.3.2. The Microflora

5.3.2.1. Algae

Algae produce mucilage that surrounds them and harbors numerous bacteria. Bacteria are microscopic unicellular organisms that develop in various environments.



Figure 26. Algae,(Example : *Caulerpa prolifera*)(Original, 2025)

5.3.2.2. Bacteria

Bacteria are microscopic unicellular organisms that thrive in various environments. Classified as prokaryotes, bacteria have a simple internal structure without a nucleus, with free DNA in a thread-like mass called a nucleoid, or in circular fragments called plasmids. Ribosomes, spherical units within the bacterial cell, assemble proteins from amino acids using ribosomal RNA. Capable of living in diverse environments, bacteria are particularly dominant in soil, significantly influencing plant growth and quality.

For example, nitrogen-fixing rhizobia, in association with legumes, fix atmospheric nitrogen, increasing the nitrogen content in plants tissues.

Plant growth-promoting rhizobacteria (PGPR) enhance yield and induce systemic resistance, preparing plants to activate their defenses against herbivorous insects.

Abundant around the roots of grasses and legumes, bacteria are divided into heterotrophs, which decompose organic matter to provide energy, and autotrophs, which oxidize or reduce mineral compounds depending on the pH and environment.

Their reactions include nitrification (conversion of NH_4 to NO_2), denitrification (reduction of nitrates to gaseous nitrogen), atmospheric nitrogen fixation, reduction and oxidation of sulfates and sulfides, as well as ferric and ferrous iron.

They play an essential role in humification, peat formation, putrefaction, and the decomposition of cellulose and sugars.

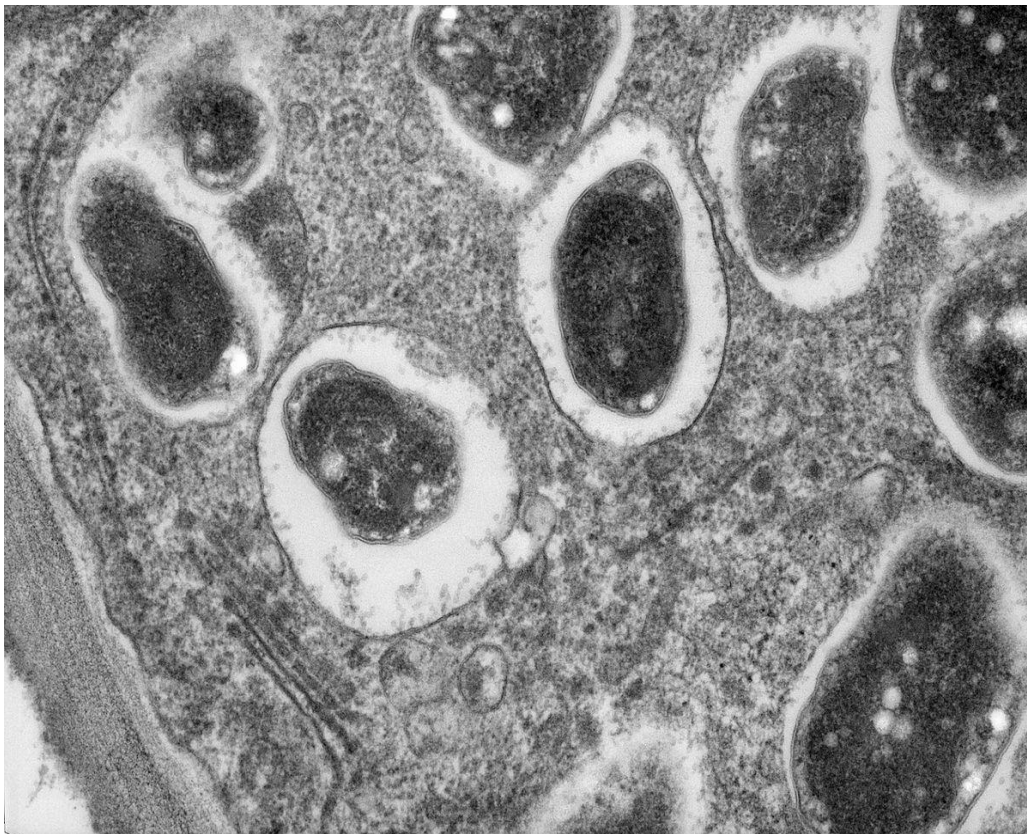


Figure 27. Bacteria (Rhizobacteria) (Original, 2025)

5.3.2.3. Actinomycetes

Actinomycetes are filamentous microorganisms characterized by non-septate mycelial structures that thrive on partially decomposed organic matter.

They play a vital role in breaking down complex substances like cellulose and chitin, contributing to nutrient cycling.

Additionally, they produce bioactive compounds, including antibiotics such as actinomycin, which help regulate microbial populations.

A key ecological function of actinomycetes is their involvement in symbiotic relationships, notably forming root nodules with certain trees, such as alders.

This symbiosis, particularly with species like *Frankia alni*, enables the active fixation of atmospheric nitrogen, enriching soil fertility and supporting plant growth.



Figure 28. Actinomycetes (Example : *Frankia alni*) (Original, 2025)

5.3.2.4. Fungi

Fungi, with their mycelium consisting of branched filaments, are primarily heterotrophic and aerobic.

Lacking chlorophyll, they reproduce through sexual or asexual methods and produce a large number of spores, ensuring a high capacity for contamination.

Morphologically, they appear as unicellular yeasts or multicellular mycelia formed of hyphae.

Metabolically, fungi are chemoheterotrophs, using organic carbon as an energy source and feeding by absorption, releasing hydrolytic enzymes into their external environment.

Fungi play a crucial role in the decomposition of organic matter, including cellulose, lignin, and tannins.

They establish symbiotic mycorrhizae with plant roots, enhancing their growth and nutrition. Soil fungi are classified into three functional groups: biological controllers, ecosystem regulators, and species involved in the decomposition of organic matter and the transformation of compounds.

Biological controllers regulate diseases, pests, and the growth of other organisms.

Ecosystem regulators are responsible for soil structure formation and habitat modification for other organisms, influencing the dynamics of physiological processes in the soil environment.

Fungi can be aero-anaerobic, with some yeasts participating in fermentation processes.

Fungal communities, rich in diversity, are composed of species with different lifestyles in ecosystems.

Based on this, fungi are classified into three major trophic levels: saprophytes, which decompose dead matter; symbiotrophs, which form symbiotic relationships; and parasites, which depend on their hosts for survival.

Thus, fungi and bacteria interact closely in the soil, with fungi contributing to the decomposition of complex organic matter, while bacteria complete this process through the mineralization of decomposition products, promoting plant growth and quality.

Fungi play a crucial role in various ecological processes and symbiotic interactions. Saprophytic fungi, for example, carry out the initial stages of decomposition of cellulose, lignin, and other complex macromolecules.

The resulting compounds from this decomposition are then processed by bacteria, making saprophytic fungi a primary driver of the decomposition process.

The hydrolytic enzymes produced by these fungi break down plant cell walls and mineralize complex compounds into simple inorganic molecules (sugars, amino acids, NH_4^+ , PO_4^{3-} , H_2O , and CO_2) that are assimilable by plants and microbes.

Simultaneously, the vast majority of plant species form symbiotic relationships between their roots and various fungal species, creating mycorrhizae.

In these associations, the fungal mycelium infects the root, enabling direct exchanges of water and nutrients.

The fungus releases enzymes, organic acids, and glycoproteins into the soil, increasing nutrient availability and contributing to soil structure while using carbon substrates provided by the plant sap as an energy source, representing a significant portion of the carbon fixed by photosynthesis.

In contrast to saprophytic fungi, parasitic fungi attack living organisms, causing diseases and sometimes the death of the host.

Most pathogenic fungi are plant parasites, often entering through natural openings or wounds. Diseases such as downy mildew, powdery mildew, smuts, rusts, apple scab, brown rot of stone fruits, as well as various leaf spots, blights, and wilts cause significant crop damage worldwide each year.

Another group of fungi, consisting of about 150 species, is capable of capturing its own prey, particularly small worms, using adhesive substances or specialized structures.

Among them, some are obligatory nematode parasites, including genera like *Purpureocillium*, *Pochonia*, *Hirsutella*, *Nematophthora*, *Arthrobotrys*, *Drechmeria*, *Fusarium*, and *Dactyellina*.

These nematophagous fungi are divided into four groups:

- Nematode-trapping fungi using specialized trapping structures
- Endoparasitic fungi using their spores
- Opportunistic fungi colonizing nematode eggs, females, or cysts with their hyphae
- Toxin-producing fungi that immobilize nematodes before invasion.

Approximately one hundred thousand known fungal species are pathogenic to humans, causing infections known as mycoses.

Most mycoses are transmitted through inhalation, ingestion, or skin wound infection, attacking the skin, hair, nails, and mucous membranes.

Spores of the genus *Aspergillus*, when inhaled, can cause a severe lung infection called aspergillosis. Infections of the skin, hair, and nails are known as ringworm.

The genus *Candida* can infect the mouth, digestive system, and reproductive system.

In newborns, this infection, called thrush, causes white patches on the oral mucosa.



Figure 29. Fungi (Example :*Boletus edulis*) (Original, 2025)

Chapter 2. The Morphological Organization of Soils

1.Elementary Organizations

Elementary organizations refer to the pedological volumes that assemble the constituents of the soil.

These organizations are partially observable to the naked eye and partially with the help of microscopes.

To the naked eye, the main observable and describable elementary organizations in observation pits are: aggregates, voids, concentrations of constituents (coatings, nodules), colors, and traces of biological activity.

The term "elementary organizations" is used in earth science to denote the spatial, functional, and genetic arrangement of soil constituents.

Elementary organizations are classified into three types: aggregates, voids, and pedological features.

1.1 .Aggregates

Aggregates result from the assembly of elementary particles and the fracturing of aggregated masses.

These aggregates associate to form clods and then layers more or less parallel to the surface, with varying thicknesses.

These layers constitute the different soil horizons.

The arrangement of these elementary particles defines the soil structure.

1.2 .Voids

Voids (or pores) are spaces largely invisible to the naked eye, located between different soil particles. These spaces are occupied by water or gases.

The morphology and volume of voids depend on numerous factors, such as the size of the soil's solid particles (clay, sand, silt, organic matter) and biological activity (animals, plants).

1.3 Pedological Features

Pedological features include nodules, coatings, bands, and pedotubules, formed by the accumulation of substances such as clay, sand, silt, calcite, carbonates, iron and aluminum hydroxides.

They also result from the formation and degradation of elements like salts and organic matter, as well as from rhizogenesis and animal movements.

Pedological features are crucial for determining soil characteristics, its stage of evolution, fertility, and porosity.

2. Soil Color

Soil color is a key indicator of variations in its composition and is one of the most visible indices for pedologists.

It is interpreted based on the mineralogical or organic constituents present in the soil.

The soil color in its dry state, observed under good lighting, is defined by reference to the Munsell international code. This code uses a combination of three variables: hue, value, and chroma.

The coloration of soil is one of its most distinctive physical properties, offering insights into its composition, formation processes, and environmental conditions. Three primary agents contribute to the diverse palette of soil colors: iron, organic matter, and limestone.

1. Iron: The Master of Soil Colors

Iron is a prevalent element in soils, primarily occurring in the form of iron oxides and hydroxides. The coloration imparted by iron varies significantly depending on the oxidation state and environmental conditions.

- **Oxidizing Conditions:**

When oxygen levels are high, iron tends to form oxides such as hematite (Fe_2O_3) and goethite (FeOOH).

These minerals produce a range of warm hues, including red, purple, rust, yellow, and brown. Such colors are typical of well-drained, aerated soils, often found in tropical and subtropical regions.

- **Reducing Conditions:**

In waterlogged or poorly aerated environments, iron exists in its reduced ferrous state (Fe^{2+}). This reduction alters its chemistry, producing bluish, greenish, or even grayish colors.

These hues are characteristic of wetland soils, where anaerobic conditions prevail.

Iron's contribution to soil color is also influenced by particle size and distribution. Finely dispersed iron oxides create subtler tones, while concentrated deposits produce more vibrant colors.

2. Organic Matter: The Black and Brown Palette

Organic matter is another critical coloring agent, responsible for the black or brown shades commonly associated with fertile soils.

- **Dark Soils:**

High levels of organic matter, such as decomposed plant and animal residues, result in rich black coloration.

These soils are typically found in grasslands or forested regions with abundant biomass.

- **Brown Soils:**

Moderate levels of organic matter produce brown hues, which indicate active but less intense organic processes.

Organic matter not only imparts color but also enhances soil fertility by improving structure, water retention, and nutrient availability.

The intensity of dark coloration often correlates with soil depth, with surface layers being richer in organic matter.

3. Limestone: The Source of White Soils

Limestone contributes to the white or pale hues in soils, primarily due to the presence of calcium carbonate (CaCO_3).

- **Calcareous Soils:** These soils often occur in arid or semi-arid regions, where low rainfall limits the leaching of calcium carbonate, allowing its accumulation in the soil profile.
- **Chalky Soils:** In areas dominated by chalk deposits, limestone imparts bright white coloration, which can reflect high sunlight levels, contributing to specific microclimatic effects.

The whiteness associated with limestone-rich soils is also indicative of limited organic matter content and reduced fertility, although such soils can be amended for agricultural use with proper management.

Interactions Between Coloring Agents

Soil color often results from the interplay of these agents. For example:

- In humic soils, organic matter may dominate, masking the contributions of iron or limestone.
- In marl or other mixed soils, the combined effects of iron oxides and calcium carbonate create unique tonal variations.
- Red soils with patches of black indicate alternating periods of oxidation and organic enrichment.

Soil Color as an Environmental Indicator

The study of soil color provides essential clues about environmental conditions:

- **Drainage and Aeration:**

Red and brown colors suggest well-drained soils, while bluish or greenish hues indicate waterlogged conditions.

- **Fertility:**

Dark soils rich in organic matter are often more fertile than pale or white soils dominated by limestone.

- **Climate and Vegetation :**

Soil color reflects the prevailing climate and vegetation types, with darker soils common in temperate and tropical regions and lighter soils in arid zones.

Thus, studying soil color not only helps to understand its composition but also to deduce information about its environmental conditions and fertility.

3. Soil Temperature

Soil temperature is a fundamental environmental variable that profoundly affects plant growth and the overall functionality of the soil ecosystem.

It exerts both direct and indirect influences on several critical soil processes, including moisture retention, aeration, soil structure, microbial and enzymatic activities, organic matter decomposition, nutrient availability, and various chemical reactions.

Understanding the dynamics of soil temperature is essential for optimizing agricultural practices, managing ecosystems, and predicting soil behavior under changing climatic conditions.

Impact on Plant Growth and Soil Ecosystem

- **Plant Growth Rates:**

Soil temperature directly influences the metabolic and physiological processes of plants, such as seed germination, root elongation, and nutrient uptake.

Optimal soil temperatures promote faster growth and development, whereas extreme temperatures can hinder these processes or even damage plant tissues.

- **Life Cycles of Soil Organisms:**

Soil temperature determines the life cycles of microorganisms, insects, and other soil-dwelling creatures.

It regulates their metabolic rates, reproduction, and interactions within the soil food web.

- **Water State in Soil:**

The temperature of the soil affects the physical state of water, determining whether it exists as a solid (ice), liquid, or vapor.

This influences water availability for plants and soil organisms.

Sources of Soil Heat

The primary sources of heat energy in soil include:

- **Solar Radiation:**

Solar energy is the dominant source of soil heating.

It penetrates the soil surface, warming the upper layers and driving temperature variations between day and night.

- **Microbial Decomposition:**

Heat generated during the microbial breakdown of organic matter contributes to soil temperature, especially in compost piles or organic-rich soils.

- **Respiration of Soil Organisms:**

The metabolic activities of soil organisms, including roots and microorganisms, release heat as a byproduct, slightly raising soil temperature.

Factors Influencing Soil Temperature

- **Terrain Slope and Relief:**

The angle and orientation of the slope affect how much solar radiation the soil receives.

South-facing slopes in the Northern Hemisphere, for example, typically receive more sunlight and are warmer than north-facing ones.

- **Soil Surface Roughness:**

A rougher soil surface with uneven textures tends to trap heat differently than a smooth surface, creating microclimatic variations.

- **Mineralogical Composition:**

The specific heat capacity and thermal conductivity of soil minerals affect how quickly soil heats and cools.

Sandy soils, for instance, warm up faster but lose heat quickly compared to clay soils.

- **Soil Moisture Content:**

Moist soils have higher thermal conductivity due to water's capacity to transfer heat.

However, wet soils also require more energy to change temperature because of water's high specific heat.

Temperature Ranges and Variability

Soil temperature varies widely based on environmental and geographical factors.

- **Desert Soils:**

Surface temperatures can exceed 50°C during the day due to intense solar radiation, making these soils inhospitable for most organisms.

- **Cold Climates:**

In winter, soil temperatures can drop below freezing, especially in regions with permafrost or seasonal frost.

This variability underscores the adaptability of plants and organisms to local soil conditions.

Relationship Between Soil and Atmospheric Temperatures

Soil temperature is closely linked to atmospheric conditions, as the soil acts as a thermal insulator between the Earth's solid crust and the air above it.

During the day, the soil absorbs heat from sunlight, warming the surface. At night, the soil loses heat to the atmosphere, cooling the surface layers.

This interplay creates diurnal and seasonal temperature fluctuations that influence soil processes.

Practical Implications

Understanding soil temperature dynamics is vital for:

- **Agriculture:**

Farmers use soil temperature data to determine planting times, optimize irrigation schedules, and enhance crop yields.

- **Soil Management:**

Mulching, irrigation, and cover cropping are strategies used to regulate soil temperature, improving conditions for plant growth and microbial activity.

- **Climate Change Adaptation:**

As global temperatures rise, monitoring soil temperature becomes increasingly important for predicting shifts in soil behavior and ecosystem responses.

By recognizing the factors that influence soil temperature and their effects on the soil ecosystem, we can better manage soil health, support sustainable agriculture, and mitigate the impacts of environmental change.

4. The Pedological Horizon

A pedological horizon is a layer parallel to the soil surface whose physico-chemical and biological characteristics differ from the layers above and below it.

Horizons, often defined by obvious physical characteristics such as color, texture, spatial arrangement of constituents, and associated voids, result from the fragmentation and weathering of parent rock under the influence of water, air, climate, as well as from the transformation and mixing with organic matter.

The description of horizons takes into account several characteristics: color, texture, thickness, granulometric composition (proportions of clays, silts, sands, and gravel), the degree of

weathering of the parent rock, the spatial arrangement of constituents (solid, liquid, gaseous), and associated voids (distribution and volume of pores).

These criteria allow for a detailed and precise classification of the different horizons, thus facilitating the study of soil structure and evolution.

4.1. Different Types of Horizons

Pedologists have developed the habit of designating horizons by capital letters.

The set of horizons constitutes the soil profile or solum.

Pedological horizons are composed of several distinct layers, each with specific characteristics.

4.1.1. The O horizon

Mainly organic, is most commonly observed in forests but often absent in other ecosystems. It includes three sub-horizons : OL (litter), consisting of raw debris identifiable to the naked eye; OF (fragmentation horizon), containing recognizable debris and fine organic matter; and OH (humified horizon), composed almost exclusively of fine organic matter transformed by soil organisms.

4.1.2. The A horizon

Is a mixed horizon located at the upper part of the soil profile, containing mineral elements and humus.

Its structure depends on the incorporation of organic matter.

4.1.3. The E horizon

Or leached horizon, is drained by infiltrated water, making it poor in ions, clays, humic compounds, and iron and aluminum hydroxides, often giving it a lighter color.

4.1.4. The B horizon

Is an intermediate accumulation horizon rich in fine or amorphous elements.

It is subdivided into BT (accumulation of clays) and BP (accumulation of organic matter and aluminum, with pellicular structure and cementation).

4.1.5. The S horizon

Is a structural horizon resulting from weathering processes, including decarbonation.

4.1.6. The C horizon

Represents the slightly weathered parent rock, while the R horizon is the unweathered parent rock, the geological layer from which soils form.

5. The Pedological Cover

The pedological cover is the soil that continuously covers the terrestrial space situated between the earth's crust (the upper part of the lithosphere) and the atmosphere.

It is in constant evolution, developing both from the parent rock and the surface organic matter.

Chapter 3. Physical and Chemical Properties of Soil

1. Physical Properties

1.1. Texture Soil

Texture is defined by the size of its constituent particles, such as gravel, sand, silt, and clay, and refers to the apparent size of particles in the fine fraction of the soil, regardless of their nature or composition.

Depending on the proportion of these different granular fractions, specific soil textures are determined.

It results from the combination of sand, silt, and clay fractions and can be characterized by the percentages of these particles in the soil.

To analyze the texture of soil, follow these steps: collect soil samples from various locations within the top few centimeters of soil; fill a transparent jar halfway with the sample; add water, leaving some air to shake the closed jar vigorously; shake well to separate the materials; shake again after one hour if necessary; let it settle for 24 hours before observation. Then, observe the following layers from top to bottom: floating matter, which is undecomposed organic matter indicating potential nutrient reserves; a layer of clay consisting of very fine particles (particle size less than 0.002 mm); a layer of silt, sometimes present, composed of particles slightly larger than clay (particle size between 0.002 mm and 0.050 mm) and generally darker; a layer of sand, distinctly differentiated (particle size greater than 0.050 mm, ranging from very fine to coarse sand); optionally followed by a layer of small gravel.

The soil type is determined using the texture triangle (Figure 30).

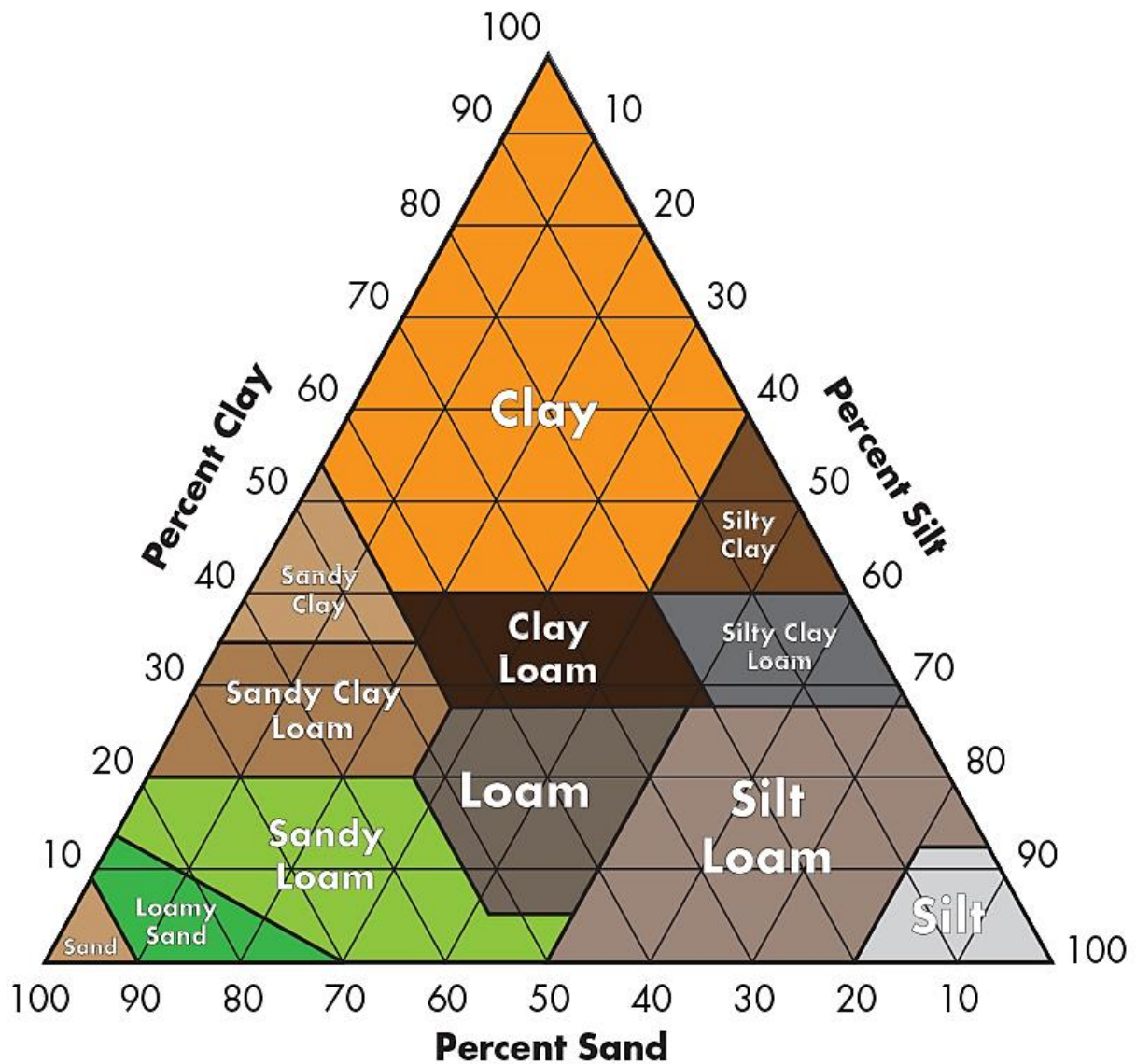


Figure 30. Texture Triangle

1.2. Structure

1.2.1. Definition of Structures

The term "structure" refers to all arrangements of the solid constituents of soil layers, between which voids persist.

Synonyms: organizations, arrangements, assemblies, configurations.

1.2.2. Origin of Soil Structures

Soil structures result from a complex interplay of physical, mechanical, biological, and chemical processes.

These processes transform loose soil particles into aggregated forms, which are critical for soil functionality, fertility, and the overall health of ecosystems.

Understanding the origin of these structures provides valuable insights into how soils develop, how they support plant growth, and how they respond to environmental changes.

1.2.2.1. Physical and Mechanical Processes

- **Weathering and Fragmentation:**

Physical weathering caused by temperature fluctuations, freeze-thaw cycles, and wind erosion breaks down larger rocks and minerals into smaller particles.

These particles, including sand, silt, and clay, form the base materials for soil structures.

- **Compaction and Pressure:**

Mechanical forces such as compaction from overlying soil layers or pressure from moving water contribute to the rearrangement and stabilization of particles, forming distinct layers or aggregates.

1.2.2.2. Biological Processes

- **Role of Plant Roots:**

Plant roots play a crucial role in the formation of soil structures.

As they grow, roots penetrate soil layers, creating pores and spaces that facilitate aeration and water movement.

Roots also release exudates, organic compounds that bind soil particles into aggregates.

- **Soil Microorganisms:**

Microorganisms such as bacteria, fungi, and actinomycetes are essential in the formation and stabilization of soil structures.

They produce polysaccharides and other organic substances that act as "glues," binding soil particles together into aggregates.

- **Soil Fauna:**

Earthworms, termites, ants, and other soil-dwelling creatures physically mix soil particles while their excretions provide organic binding agents.

This bioturbation enhances aggregation and the development of stable soil structures.

1.2.2.3. Chemical Processes

- **Cation Exchange:**

Clay minerals and organic matter possess a high cation exchange capacity (CEC), which facilitates the bonding of soil particles.

Cations like calcium, magnesium, and aluminum serve as bridges between negatively charged particles, promoting aggregation.

- **Organic Matter and Humus:**

The decomposition of organic material results in humus, a stable organic compound that binds mineral particles.

This process not only enhances soil structure but also increases its water retention and nutrient-holding capacities.

- **Precipitation of Minerals:**

Chemical reactions involving soluble minerals like calcium carbonate or iron oxides contribute to the formation of stable aggregates by acting as binding agents.

1.2.2.4. Environmental Influences

- **Rainwater and Moisture:**

Water plays a dual role in soil structure formation.

On one hand, it dissolves minerals and distributes organic matter; on the other, it facilitates the movement and deposition of particles.

The drying and wetting cycles caused by rainfall create stresses that promote aggregation.

- **Atmospheric Conditions:** Temperature variations and seasonal changes influence the soil's physical properties. For example, freezing and thawing can create cracks and fissures that help define soil structure.

1.2.2.5. Contribution of Primary and Secondary Minerals

Soil minerals play a foundational role in the development of soil structures.

- **Primary Minerals:**

Derived directly from the parent rock, primary minerals such as quartz and feldspar contribute to the granular framework of the soil.

- **Secondary Minerals:**

Formed through weathering processes, secondary minerals like clays and iron oxides act as binding agents in the aggregation process.

- **Interaction of Organic Matter and Minerals**

The combination of organic matter with mineral particles is central to soil structure formation. Organic matter acts as a binding agent, while minerals provide the structural framework. Together, they form stable aggregates, which enhance the soil's porosity, permeability, and resistance to erosion.

1.2.3. Significance of Soil Structures

The development of soil structures is essential for:

- **Plant Growth :**

Structured soils offer an optimal environment for root development, water infiltration, and nutrient availability.

- **Water Management :**

Well-aggregated soils retain water efficiently, reducing runoff and promoting groundwater recharge.

- **Erosion Control :**

Stable soil aggregates resist erosion by wind and water, protecting the soil surface and maintaining its fertility.

- **Carbon Storage :**

Soil structures contribute to carbon sequestration by trapping organic matter within aggregates, reducing its decomposition rate and mitigating climate change.

1.3. Classification of Soil Structures

Soil structure classification provides insights into how particles are organized within the soil, which has significant implications for soil properties, water movement, and biological activity. The classification broadly categorizes structures into **apedal structures** (without aggregates) and **pedal structures** (with aggregates), each characterized by specific formation processes and physical attributes.

1.3.1. Apedal Structures (Absence of Aggregates)

Apedal structures are marked by the absence of cohesive aggregates.

Instead, the soil particles exist in a dispersed or uniform state, often due to specific environmental and material conditions.

1.3.1.1. Particulate Structure

This structure emerges when there is a complete lack of cohesion between the soil particles.

- **Composition:**

Commonly found in materials like sands, gravels, and occasionally sandy silts or chalky soils.

- **Characteristics:**

The particles remain loose and do not form any noticeable aggregates.

Such soils are highly permeable, facilitating rapid water infiltration but often limiting water retention and nutrient availability.

- **Occurrence:**

Predominant in arid or sandy environments where organic or mineral cements are absent.

1.3.1.2. Massive or Continuous Structure

Massive or continuous structures are characterized by a coherent assembly of soil particles without distinct planes of separation or aggregation.

- **Formation:**

This type lacks flocculated clay-humic cements that typically form aggregates. However, diffuse mineral cements, such as iron oxides, calcium carbonate, or silica, may coat particles, providing a degree of cohesion.

- **Appearance:**

Often found in fine-textured soils like silts or silty clays.

These soils may form crusts or hardened layers known by names such as *crusts*, *casings*, *armours*, or *alios*.

- **Environmental Relevance:**

Such structures can impede root penetration and water infiltration, leading to waterlogging or runoff in certain conditions.

1.3.1.3. Fibrous (or Granular) Structures

Fibrous structures arise when a soil horizon is composed entirely of organic material.

- **Composition:**

Consists of plant fibers, partially decomposed organic matter, leaf litter, or excretions from soil mesofauna.

- **Functionality:**

These structures are highly porous, promoting water retention and aeration, but may vary significantly depending on the degree of decomposition.

- **Typical Locations:**

Commonly observed in organic-rich environments such as peatlands, forest floors, or compost layers.

1.3.2. Pedal Structures (With Aggregates)

Pedal structures exhibit the presence of aggregates, which are clusters of soil particles bound together by physical, chemical, or biological processes.

These structures enhance soil functionality, improving aeration, water retention, and root penetration.

1.3.2.1. Constructed Structures

Constructed structures are formed through biological activity.

- **Formation Agents:**

Soil organisms like bacteria, fungi, earthworms, and other fauna produce organic and inorganic substances that act as natural cements.

- **Characteristics:**

The resulting aggregates are stable and highly porous, promoting optimal conditions for plant growth and microbial activity.

- **Ecological Impact:**

These structures are crucial for nutrient cycling, water infiltration, and erosion control, often serving as indicators of healthy soils.

1.3.2.2. Mechanical Structures

Mechanical structures form due to physical or non-biological processes.

- **Formation Processes:**

- **Desiccation:**

Soil drying leads to shrinkage and cracking, creating distinct aggregates.

- **Frost Action:**

Freezing and thawing cycles cause soil expansion and contraction, breaking up larger masses into aggregates.

- **Root Growth:**

Expanding root systems exert pressure on soil particles, causing physical rearrangement and aggregation.

- **Human Activities:**

Mechanical soil tillage or plowing can also create temporary aggregates.

- **Material Sources:**

Often observed in originally massive materials like marl, loess, or clayey alluvium.

- **Environmental Importance:**

Mechanical structures help improve soil aeration and water infiltration but may be less stable than biologically formed aggregates, particularly under adverse climatic conditions.

1.3. Actual Density, Apparent Density, and Porosity

1.3.1. Actual Density

This correspond to the density of its constituent elements and remains constant.

$$\text{Actual Density ACD (g/cm}^3\text{)} = \text{Ms/Vs}$$

1.3.2. Apparent Density

This takes into account the voids existing between these elements, which vary according to the degree of fissuring or compaction.

$$\text{APD (g/cm}^3\text{)} = \text{Ms/Vt}$$

Both apparent and actual densities allow the deduction of the proportion of voids or porosity.

1.3.3. Porosity

Porosity is the volume of the soil not occupied by solid matter.

$$\text{Porosity (\%)} = ((\text{Ve} + \text{Va}) / \text{Vt}) \times 100$$

Where :

Ms : mass of solids

Vs : volume of solids

Vt : total volume of the sample

Ve : volume of water

Va : volume of air

2. Chemical Properties

2.1. Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) is the total amount of cations that a certain weight of soil (usually 100 grams) can fix on its clay-humic complex and exchange with the soil solution at a given pH.

In other words, it is the sum of the negative charges of the soil available to fix H⁺ and Al³⁺ ions as well as the basic cations Ca²⁺, Mg²⁺, Na⁺, and K⁺.

The CEC depends on the nature of the colloids, which have a variable and specific number of negative sites, as well as on the soil pH.

The mechanism of cation exchange depends on the nature of the ions. The fixation of ions on the clay-humic complex follows a preferential order.

The cations usually fixed on this complex mainly include H⁺ ions and metallic cations. Among these, some are fixed in significant quantities, such as Ca²⁺, Mg²⁺, and K⁺, while others, like NH⁴⁺, Mn²⁺, Zn²⁺, Cu²⁺, Fe²⁺/Fe³⁺, and Al³⁺, are generally fixed in more limited quantities.

The retention intensity of these ions varies according to a specific order: for anions, SO₄ > F > NO₃ > Cl > Br, and for cations, Li < Na < Mg < Ca < Ba < Al < H. Thus, a cation can be displaced by all those located to its right in this order.

Several factors influence the cation exchange capacity (CEC) of the soil.

First, soil texture plays an important role: the CEC increases with the fineness of soil particles, meaning a higher clay content increases the CEC.

A decrease in particle size leads to an increase in specific surface area per unit volume, thus increasing the net charge and CEC.

Second, organic matter also contributes to an increase in CEC.

The pH-dependent charges in organic matter cause a variation in CEC: as the pH of the soil solution increases, the CEC also increases.

Third, the nature of the clay is a determining factor: soils dominated by montmorillonite and vermiculite have a higher CEC than those dominated by kaolinite, chlorite, or illite.

Finally, the soil solution influences the CEC, which generally increases with increasing soil pH. The increase in pH leads to an increase in the pH-dependent charge, and in humus, most of the CEC depends on the pH.

2.2. Anion Exchange Capacity (AEC)

The anion exchange capacity (AEC) is the capacity of soil particles to adsorb and store anions, measured in meq/100g of soil.

Common soil anions include chloride (Cl⁻), nitrate (NO₃⁻), sulfate (SO₄⁻), and phosphate (PO₄³⁻).

Anions can have more than one negative charge and be combinations of elements with oxygen. PO₄³⁻ anions are particularly well retained.

The energy of anion fixation follows the decreasing order: PO₄³⁻ > SO₄⁻ > NO₃⁻ > Cl.

This fixation is due to several mechanisms: adsorption on iron and aluminum hydroxides, positive colloids linked to clay, in exchange for OH⁻ ions; fixation on a few positive valences of clays in exchange for OH⁻ ions; and fixation on clay or humus via Ca⁺⁺ ions (calcium bridges).

2.3. Soil pH

The acidity and alkalinity of an aqueous solution are described by the term pH, which is the negative logarithm of the hydrogen ion concentration [H⁺]. Hydrogen, a component of all acids, ionizes to form [H⁺] ions, whose concentration determines the acidic properties of soil solutions. pH is calculated as follows:

$$\text{pH} = -\log[\text{H}^+] = \log 1/[\text{H}^+].$$

Soil acidity is defined by the concentration of H⁺ ions, mainly derived from biological activities. In soil, H⁺ ions are distributed between those present in the soil solution and those fixed on colloids in an exchangeable state.

Sources of H⁺ ion production include hydrogen atoms from organic acids and H⁺ ions from the reaction between CO₂, produced by soil fauna, root respiration, and the decomposition of organic matter.

Soil pH is commonly measured with a pH meter using glass and reference electrodes.

Several factors influence soil pH: the parent material (soils formed from sandstone or shale are more acidic than those formed from limestone), precipitation (which increases the leaching of Ca and Mg, thereby reducing pH), native vegetation (grassland soils are less acidic than forest soils, and coniferous residues are more acidic than deciduous residues), agricultural practices (legumes remove more calcium and magnesium, increasing H⁺ ions and lowering pH), and the use of fertilizers (acidifying nitrogen and phosphate fertilizers lower pH, except those containing compensatory base supports).

Irrigation water, often rich in dissolved calcium and magnesium, can also influence pH by offsetting the acidifying effects of fertilizers or organic matter.

2.4. Saturation Rate

By analyzing these different parameters, the saturation rate (V) can be calculated, indicating the current state of the exchange complex relative to its maximum capacity. The formula used for this measurement is as follows :

$$V=(S/T)\times 100$$

Where :

V: saturation rate (%)

S: sum of alkali and alkaline-earth metals (cmolc/kg)

T: cation exchange capacity (cmolc/kg)

However, the saturation rate varies according to the type of cation exchange capacity (CEC). Only considering soil pH can reflect the current state of the exchange complex.

A soil is said to be saturated when S = T.

In this case, no acid ions are present, as in a soil with a high calcium reserve. In practice, for other soil types, a soil is generally considered saturated when the rate reaches 85-90%.

If not, the soil is considered unsaturated, allowing acid ions to become predominant on the surface of the exchange complex.

2.5. Sodicty

The previously mentioned Na⁺ cation plays a significant role in certain soils, called sodic soils.

In excess, this element can destabilize soils by causing repulsion between clay particles, making the soil impermeable and hindering root penetration.

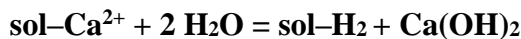
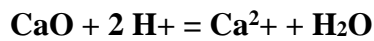
Sodicity measures the proportion of exchangeable Na⁺ relative to the total exchangeable cations, according to the following formula :

$$\text{Sodicity} = (\text{Exchangeable Na}^+ / \text{CEC}) \times 100.$$

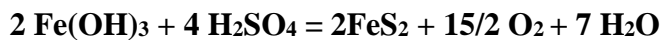
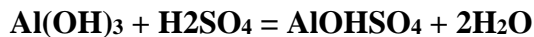
2.6. Buffering Capacity and Acidification

The soil has a natural resistance to pH variation, known as buffering capacity. This buffering capacity is stronger when the soil has a high cation exchange capacity (CEC), thanks to clay-humic colloids and clays, which favor the reserve of nutrient ions.

Carbonates (CaCO₃) present in calcareous soils, as well as lime (CaO), serve as reserves of Ca²⁺ for the CEC, thereby neutralizing soil acids.



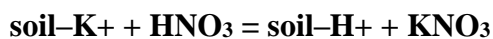
Aluminum (Al) and iron (Fe) can also complex acids, such as H₂SO₄:



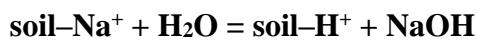
Iron hydroxides can also form at lower pH values (around pH=2).

For soils that are neither carbonate-rich nor high in aluminum or iron, a buffering effect from basic ions, such as K⁺, can be observed.

This effect again depends on the cation exchange capacity (CEC).



The nature of basic cations does not affect the pH, except for the Na⁺ ion present in sodic soils, which increases pH through hydrolysis, potentially exceeding 9.



2.7. Specific Adsorption

In chemistry, adsorption is a surface phenomenon where atoms, ions, or molecules (adsorbates) attach to a solid surface (adsorbent) between two phases (gas-solid, gas-liquid, liquid-solid, liquid-liquid, solid-solid).

The substance adsorbed is the adsorbate, and the material adsorbing is the adsorbent.

The properties of adsorbates and adsorbents are specific and depend on their constituents. If the interaction between the solid surface and the adsorbed molecules is physical, it is called physisorption.

In this case, the attractive interactions are van der Waals forces and, being weak, make the process reversible. If the attractive forces between the adsorbed molecules and the solid surface are due to a chemical bond, the process is called chemisorption.

2.7.1. Phosphate Adsorption

Phosphorus (P) attracts particular attention as a non-renewable resource. In many agricultural systems requiring phosphorus application to ensure plant productivity, phosphorus recovery by crops during a growing season is very low.

More than 80% of P becomes immobile and unavailable for plant uptake due to adsorption, precipitation, or conversion to organic form.

A unique characteristic of phosphorus is its low availability, attributed to its slow diffusion and strong fixation in soils.

The main factors influencing these reactions include the phosphorus concentration in solution, the amount of iron and aluminum oxides, the type and amount of clay, soil pH, and organic matter.

Aluminum oxides, iron oxides, and clay silicates are well-known phosphate adsorbents in soils. In acidic soils, phosphorus can be primarily adsorbed by Al/Fe oxides and hydroxides, such as gibbsite, hematite, and goethite .

Phosphorus is first adsorbed on the surface of clay minerals and Fe/Al oxides, forming various complexes.

Clay minerals and Fe/Al oxides have large specific surfaces, offering a significant number of adsorption sites.

2.7.2. Specific Adsorption of Phosphorus by Aluminum and Iron Oxides

The process of phosphate adsorption by aluminum and iron oxides, known as adsorbents, is referred to as specific adsorption.

The adsorbed phosphate molecule or ion is called the adsorbate.

Specific adsorption of ions can occur on uncharged adsorbents and sometimes even on surfaces with a similar charge to that of the adsorbate.

The reactive sites of these amphoteric minerals, AlOH and FeOH, are the hydroxyl groups exposed on the mineral surfaces.

The singly coordinated hydroxyl groups can be quantitatively replaced or exchanged by phosphate anions, leading to the formation of a binuclear or surface complex for the iron oxide-phosphate system. This process is accompanied by the release of hydroxyl groups (OH⁻) and water molecules (H₂O).

The precise nature of these reactions depends on the pH, which influences the proportions of hydroxyl groups (OH⁻) and OH²⁺ on the solid surface, and consequently, its surface charge. The adsorbed phosphate can be trapped on the soil mineral surface if a coating of Fe or Al oxide precipitates on the mineral.

Chapter 4. Soil Classification

Soil classification aims to group soils into categories with similar characteristics. Given the diversity of soils and their numerous physical, chemical, and biological properties, this classification facilitates the organization and communication of soil information.

It also helps to better understand the relationships between soils and environmental factors.

This classification is hierarchical, using classes, subclasses, groups, subgroups, families, series, and phases.

Soil classification is designed as a reference system for organizing the soils described in a study and the units on a map according to a common plan. It also defines a common language for professionals in the field.

1. The French Soil Classification

The French soil classification, established in 1967 by the Commission de Pédologie et de Cartographie des Sols (CPCS), is hierarchical and morphogenetic.

It includes several levels: class, subclass, group, subgroup, family, series, type, and phase.

Soils grouped in the same class share certain major characteristics: a certain degree of profile development or soil evolution, a mode of mineral alteration related to general physicochemical conditions, a typical composition and distribution of organic matter influencing soil evolution and horizon differentiation, and predominant fundamental factors of soil evolution, such as the presence of water (hydromorphy) or highly soluble salts (halomorphy).

Subclass differentiation relies, where possible, on criteria resulting from pedo-climatic conditions.

For example, the limited evolution of poorly developed soils can be due to a very cold or dry and hot climate.

The French classification uses the following classes:

1.1. Raw Mineral Soils

Soils with an (A)C, (A)R, or R profile have no agronomic value due to the absence of mineral evolution and their lack of organic matter.

These soils contain only traces of organic matter in the top 20 centimeters and/or no more than 1 to 1.5% in the top 2-3 centimeters.

The mineral matter undergoes more or less mechanical disintegration and fragmentation, but chemical alteration remains insignificant.

An example of this category is the subclass of raw climatic mineral soils of cold deserts (Cryosols bruts), such as the Lithosols of cold deserts.

1.2. Slightly Developed Soils

Soils with an AC profile, where the surface horizon is an A horizon sometimes rich in organic matter, contain more than traces of organic matter in the top 20 centimeters and/or more than 1 to 1.5% of organic matter over more than 2 to 3 centimeters.

Some of this organic matter may be well humified.

Although the mineral matter has not undergone significant chemical alteration, it may have been disintegrated and fragmented by physical phenomena.

For example, the release of iron and the sericitization of feldspars indicate partial alteration. An example of this category is the subclass of slightly developed soils with permafrost, belonging to the group of soils with high ice segregation.

1.3. Calcomagnesian Soils

Soils whose morphological characteristics of the upper horizons are determined by the presence of alkaline earth ions have several peculiarities.

The lower part of the solum, when present, shows neither the characteristics of vertisols nor those of isohumic soils.

The clays present are of the 2/1 type, and the complex is more than 90% saturated with calcium or magnesium, with a pH greater than 6.8.

These soils have a superficial horizon relatively rich in organic matter intimately linked to limestone and silicate elements. Although deep horizons may exist, they are limited to B and C horizons.

Calcium and magnesium carbonates and sulfates are present, and the soil is saturated with divalent cations.

However, these soils are characterized by a deficiency in nitrogen, insoluble calcium phosphorus, and trace elements. An example of this category is the subclass of carbonate soils, belonging to the group of calcareous brown soils.

1.4. Vertisols

Soils that are quite dark in color, sometimes black, have distinctive characteristics. The clay proportion is often above 30%, largely composed of swelling clay, usually montmorillonite. These soils are sticky when wet, while their surface structure is finely polyhedral when dry. They are compact and their usable water content is low during the dry season but high during the wet period.

These soils exist under various climates, provided that precipitation is less than 1500 mm. Although chemically rich, their physical properties limit usage possibilities, despite a high exchange capacity.

Soils with A(B)C, A(S)C, or A(B)C profiles are more or less homogenized or irregularly differentiated due to internal movements, manifested by the presence of large aggregates, microrelief, and subsidence.

Their horizons differentiate only by their structure.

These clayey soils, dominated by swelling clays whose proportions often reach 35-40%, have an average exchange capacity of 35 to 40 meq.

Their color is generally dark, related to their organic matter content.

An example of this category is the subclass of vertisols with possible external drainage, belonging to the group of vertisols with null external drainage and rounded structure in at least the top 15 centimeters.

1.5. Isohumic Soils

These are developed soils with moderately or slightly differentiated profiles of the A(B)C type, sometimes AC, displaying distinct characteristics.

The B horizon is typically characterized by its structure and may be more clayey than the A horizon, while the profile is rarely of the AC type.

The horizons, clearly marked by organic matter, constitute a significant part of the soil profile, representing at least half of the soil profile down to its original material.

The adsorbing complex of these soils is primarily saturated with calcium, and secondarily with magnesium.

An example of this category is the subclass of isohumic soils, belonging to the group of brunizems. These soils have an organic matter content that decreases very gradually with depth, but this content remains significant even in the deeper horizons.

They contain calcareous humus, rich in nitrogen and gray humic acids primarily derived from roots. They exist in climates with a dry season, between the 15th and 45th degrees of latitude, and are characterized by intense biological activity, involving microorganisms and small rodents.

1.6. Podzolized Soils

Soils with coarse humus have several distinctive characteristics.

They are often topped with a layer of raw humus and, deeper down, a complex horizon enriched with dark brown humus well bonded to the mineral matter and sesquioxides of iron, rusty ochre, as well as alumina derived from the alteration of original minerals and clays.

This class includes soils often formed under the influence of mor-type humus, or possibly moder-type humus.

The large quantities of fulvic acids released are responsible for significant silicate alteration, up to the destruction of clays, and major iron and aluminum complexation.

An example of this category is the subclass of podzolized soils in temperate climates, belonging to the group of Podzols.

1.7. Brownified Soils

Soils developed under the action of rapidly decomposing organic matter present several distinct scientific characteristics.

The humus formed contains a limited proportion of insoluble compounds that complex with clay and form unstable aggregates, sometimes allowing clay migration. However, this phenomenon is limited by the rapid mineralization of the humus.

Iron, available in the form of hydroxides, never fully dehydrates. The complex association of clay-humus-iron gives the soil a brown color.

These soils primarily form in temperate regions.

These evolved soils are characterized by humus with high biological activity, generally of the mull type, but sometimes of the moder type at the class boundaries.

The typical profile is of the A(B)C or ABC type, where the B horizon is sometimes difficult to distinguish.

The textural B horizon or structural (B) horizon is poor in organic matter, with a C/N ratio below 14.

An example of this category is the subclass of brownified soils in humid temperate climates, belonging to the group of brown soils.

1.8. Sesquioxide-Rich Soils

Soils with ABC or A(B)C profiles are characterized by several distinctive traits. They display a marked individualization of iron (or manganese) sesquioxides, giving them a very pronounced color: red, rusty ochre, or even black if manganese oxides are abundant.

This coloration may be present in both the A and B horizons, but more frequently only in the B horizons.

The base saturation rate of these soils is above 50%, while their organic matter content is generally low, often undergoing rapid decomposition.

An example of this category is the subclass of ferruginous (tropical) soils, belonging to the group of minimally leached tropical ferruginous soils, with a leaching index of 1/1.4.

These soils are particularly rich in metallic sesquioxides, mainly iron, but sometimes also aluminum and manganese.

They often contain black, red, or purple metallic concretions, as well as variously colored crusts or hardpans, more or less hardened, and their fragmentation products such as blocks, pebbles, and gravel.

1.9. Ferralitic Soils

Characterized by the complete alteration of primary minerals such as peridotites, pyroxenes, garnets, amphiboles, feldspars, feldspathoids, and micas.

They contain aluminum silicates (kaolinite), aluminum hydroxides (gibbsite, rarely boehmite and amorphous products), as well as iron hydroxides and oxides (hematite and amorphous products).

These soils have a low exchange capacity, whether for clay or the total soil, due to the presence of kaolinite and sesquioxides, making it difficult to specify a precise value limit.

They also have a low amount of exchangeable bases, a variable but generally low degree of saturation, and an acidic pH.

1.10. Sodic Soils

Characterized by evolution dominated either by the presence of soluble salts (chlorides, sulfates, carbonates, bicarbonates of sodium and/or magnesium), whose high content may be visible to the naked eye and significantly alter the vegetation. The conductivity of the saturated paste extract of these soils is greater than 7 mmhos/cm at 25°C, affecting the entire profile for part of the year.

Alternatively, by the presence of exchangeable sodium (and/or magnesium), leading to a massive and diffuse structure and high compaction.

In this case, sodium occupies more than 10% of the exchange capacity. This phenomenon is observed in soils whose texture is too light to allow the creation of a saturated paste.

1.11. Hydromorphic Soils

Characterized by evolution dominated by the effect of excess water, resulting from temporary or permanent waterlogging of part or all of the profile.

2. The American Soil Classification System

The **American Soil Classification System**, formally known as the **United States Soil Taxonomy**, is a detailed framework developed by the USDA Natural Resources Conservation Service (NRCS) to categorize soils based on their observable and measurable properties.

This system is widely used in the United States and serves as a reference globally for soil research, agriculture, and environmental management.

It organizes soils into a six-level hierarchy: **Order, Suborder, Great Group, Subgroup, Family, and Series**, ranging from the broadest to the most specific classification.

The system focuses on diagnostic horizons, soil moisture regimes, temperature regimes, and other physical and chemical properties.

The U.S. Soil Taxonomy is essential for agriculture, helping to determine soil fertility, drainage, and suitability for specific crops.

It also guides land management decisions, such as erosion control, wetland preservation, and urban development.

The system facilitates international collaboration by aligning with global frameworks like the World Reference Base for Soil Resources (WRB) and FAO-UNESCO Soil Classification.

The highest category in Soil Taxonomy is the **Order**, representing major soil groups with distinct formation processes and characteristics:

Diagnostic criteria include diagnostic horizons (epipedons), pedoclimate, and secondary criteria representing distinct pedological properties.

This classification primarily relies on the presence or absence of different horizons.

2.1. Gelisols (Greek "gelid" = very cold)

Have permafrost at the surface or at least before 200 cm depth, typical of minimally developed soils in high altitudes and latitudes.

Are soils with permafrost or evidence of freezing and thawing processes (cryoturbation) within 2 meters of the surface.

These soils are typical of Arctic and tundra regions, such as Alaska.

2.2. Histosols (Greek "histos" = tissue)

Feature a thick organic horizon (more than 40 cm or more than 2/3 of the soil thickness if the soil is shallow), with accumulation related to the current or past presence of water (peats and very organic soils).

Are organic-rich soils that develop in wetlands.

They consist largely of decomposed plant material (peat or muck) and are common in areas like Florida's Everglades.

2.3. Spodosols (Greek "spodos" = ashes)

Have a spodic horizon, characteristic of podzolized soils typical of highly acidified environments.

Are acidic soils with a spodic horizon, enriched in organic matter and aluminum/iron compounds.

These soils are found under coniferous forests in cooler climates, such as the northeastern U.S.

2.4. Andisols (Japanese "ando" = black)

Display andic properties, typical of volcanic regions if the environment is humid and cool or cold.

Are soils formed from volcanic ash. They have high water retention and nutrient availability and are common in regions with volcanic activity, such as the Pacific Northwest.

2.5. Oxisols (French "oxide")

Feature an oxic horizon (less than 10% weatherable minerals in the 50-200 micron fraction, presence of sesquioxides such as Fe_2O_3 or Al_2O_3 , exchange capacity less than 16 cmol(+) per kg of clay) or a kandic horizon: fine texture, relative enrichment in clay, limited exchange capacity, typical of ferralitic soils in intertropical zones.

Are highly weathered tropical soils with low fertility.

They are rich in iron and aluminum oxides and are rare in the United States, occurring mainly in Hawaii and Puerto Rico.

2.6. Vertisols (Latin "vertos" = to turn, soils that move)

Have slickensides or at least aggregates with oblique faces, more than 30% clay, and shrinkage cracks during dry periods, typical of vertisols in dry Mediterranean or subtropical climates.

Are clay-rich soils that shrink and swell with changes in moisture, causing deep cracks.

These soils are common in regions like Texas and the Mississippi Delta.

2.7. Aridisols (Latin "aridus" = dry)

Correspond to an arid climate, regardless of high or low temperatures.

They may be water-saturated if salty.

Possible diagnostic horizons: natric, calcic, petrocalcic, gypsic, petrogypsic, salic, argillic, duripan, typical of soils in dry climates with accumulations of calcium, gypsum, or salts.

Develop in arid climates, characterized by limited organic matter and accumulations of salts, gypsum, or carbonates.

They are widespread in deserts, particularly in the southwestern United States.

2.8. Ultisols (Latin "ultimus" = ultimate)

Show signs of advanced development: argillic, kandic, or fragipan horizon and base saturation rate below 35%, typical of highly weathered soils in intertropical and subtropical zones.

Are weathered soils with low base saturation and a clay-enriched subsurface horizon.

They are common in the southeastern United States, where warm and humid climates prevail.

2.9. Mollisols (Latin "mollis" = soft, soils with soft humus)

Have a mollic surface horizon with a base saturation rate over 50%, typical of soils in prairies and deciduous forests, whether calcareous or not.

Are highly fertile soils characterized by a thick, dark, humus-rich surface layer (mollic epipedon).

They are common in grassland regions like the Great Plains and are widely used for agriculture.

2.10. Alfisols (invented term)

Feature an argillic, kandic, natric horizon or a fragipan. Found in humid or subhumid climates, base saturation rate over 30%, slightly acidic, typical of leached soils in humid climates.

Are fertile soils found in moderate climates, often under deciduous forests. They have a subsurface clay-enriched horizon (argillic horizon) and high base saturation, making them productive for agriculture.

2.11. Inceptisols (Latin "inceptum" = beginning)

Do not fall into the above categories due to being relatively shallow and not followed at depth by calcic, petrocalcic, gypsic, petrogypsic, placic, duripan, fragipan, oxic, spodic, sulfuric horizons.

However, they may feature horizons corresponding to slightly developed soils: cambic, histic, mollic, plaggen, umbric epipedon.

Represent soils with weakly developed profiles, more advanced than Entisols.

They are found in diverse environments, including mountainous regions.

2.12. Entisols

Do not fit into any of the previous categories.

They lack developed diagnostic horizons except for ochric and anthropic epipedons, typical of raw mineral soils.

Are young soils with minimal profile development, often found in areas of recent sediment deposition, such as floodplains or dunes.

3.The Russian Soil Classification System (RSCS)

The RSCS is widely used in agriculture, environmental studies, and land management. Its focus on soil genesis and properties allows it to align with international systems like the FAO-UNESCO Soil Classification and the World Reference Base for Soil Resources (WRB).

The Russian Soil Classification System (RSCS) is a detailed framework for categorizing soils based on their genesis, properties, and processes, and it has evolved over decades to address the specific conditions of Russia's diverse climate and geography.

The RSCS organizes soils hierarchically into categories: classes, types, subtypes, genera, and species.

3.1. Key Soil Classes and Types

3.1.1 Zonal Soils

Zonal soils are formed under specific climatic and vegetation zones.

They reflect the dominant influence of the climate and vegetation over time, making them representative of particular ecosystems.

3.1.1.1 Podzols

Podzols are acidic soils commonly found in coniferous forest regions and cold climates.

These soils are characterized by an **eluvial horizon** (E horizon) rich in silicates due to leaching and a **subsoil horizon** (spodic horizon) where iron, aluminum, and organic matter accumulate. Their low nutrient content and acidic nature make them challenging for agriculture without significant amendments.

3.1.1.2 Chernozems

Chernozems are among the most fertile soils globally, recognized for their high organic matter content and thick, dark humus-rich topsoil (A horizon).

These soils are prevalent in **steppe regions** with grassland vegetation, supporting intensive agriculture, particularly cereal crops.

3.1.1.3 Chestnut Soils

Chestnut soils are found in semi-arid regions and are less fertile than Chernozems. While they have some organic matter, their levels are moderate, and they often feature a calcium carbonate-enriched subsurface layer. These soils are suitable for grazing and certain crops with appropriate irrigation.

3.1.2 Intrazonal Soils

Intrazonal soils develop under local conditions where factors such as parent material, drainage, or salinity play a dominant role, overriding broader climatic influences.

3.1.2.1 Solonchaks

Solonchaks are saline soils typical of arid and semi-arid regions. They are characterized by high concentrations of soluble salts, poor structure, and low fertility. Their saline nature makes them unsuitable for most crops without desalination or other reclamation measures.

3.1.2.2 Solonetz

Solonetz soils are defined by a sodium-enriched subsurface horizon, often accompanied by high pH levels.

This sodium accumulation leads to poor structure and drainage, forming a hardpan that restricts root penetration. Reclamation efforts such as gypsum application are often necessary to improve their agricultural potential.

3.1.3 Azonal Soils

Azonal soils are minimally developed and strongly influenced by parent material or recent sediment deposits.

They lack a well-defined profile due to their youth or environmental constraints.

3.1.3.1 Alluvial Soils

Alluvial soils form along riverbanks and floodplains from sediment deposition during periodic flooding.

These soils are typically fertile, with stratified layers reflecting the depositional history.

They are extensively used for agriculture due to their high nutrient availability and good drainage.

3.1.3.2 Lithosols

Lithosols are thin, underdeveloped soils that form over hard rock.

They have limited profile development, often consisting of a thin organic layer over the bedrock.

These soils support sparse vegetation and are unsuitable for most agricultural purposes due to their shallow depth and low fertility.

Chapter 5: Overview of Algerian Soils

Algerian soils exhibit considerable diversity due to the country's varied climate, topography, and geological history.

The classification of these soils reflects their formation processes and environmental influences, divided into four main categories : **Saharan Soils, Soils of Semi-Arid Regions, Soils of Humid Regions, and Azonal Soils.**

1. Saharan Soils

In the vast expanse of the Sahara Desert, soil formation is dominated by extreme climatic conditions, particularly aridity and the influence of wind.

The wind's erosive and depositional activity plays a crucial role in shaping these soils, which are primarily aeolian (wind-formed) in origin.

There are two principal types of aeolian soils in this region:

1.1 Ablation Aeolian Soils

Ablation aeolian soils are characterized by the absence of fine earth particles due to wind erosion.

This results in a surface layer dominated by coarse pebbles, which are more resistant to wind erosion and often form a protective layer known as "desert pavement.

These soils are typically nutrient-poor and unsuitable for conventional agriculture.

1.2 Accumulation Aeolian Soils

Accumulation aeolian soils consist of sand deposits formed by wind activity.

These deposits vary in development, ranging from loose, unconsolidated sand to more stabilized dunes.

Their texture and limited organic content make them poorly suited for vegetation without significant intervention, such as irrigation or windbreaks.

2. Soils of Semi-Arid Regions

In Algeria's semi-arid regions, soils are primarily influenced by moderate aridity and the presence of limestone or gypsum in the parent material.

These soils can be categorized into:

2.1. Calcareous Soils

Derived from limestone, these soils are rich in calcium carbonate and generally exhibit poor water retention.

They often require significant soil amendments for agricultural use.

2.2. Gypsiferous Soils

Containing gypsum, these soils are typically found in arid and semi-arid areas.

While gypsum can enhance soil structure in moderate amounts, excessive gypsum content can limit fertility and plant growth.

2.3. Saline Soils

These soils, though less common in this category, are characterized by the presence of soluble salts that may restrict plant growth.

3. Soils of Humid Regions

In Algeria's humid regions, typically found along the northern coastal and mountainous zones, soils exhibit greater development due to higher precipitation and vegetation cover.

The primary soil types include :

3.1. Calcareous Soils

These soils are formed from limestone rocks and are rich in calcium carbonate.

They support diverse vegetation but may require management for improved water and nutrient availability.

3.2. Non-Calcareous Soils

Formed from non-limestone parent material, these soils generally exhibit greater weathering and nutrient variability.

3.3. Mediterranean Red Soils

These heavily rubefied (reddish) soils are a hallmark of Mediterranean climates. Their red coloration results from iron oxide accumulation, and they are typically well-drained and moderately fertile, supporting agriculture in many regions.

4. Azonal Soils

Azonal soils in Algeria encompass a wide variety of soils that lack significant horizon development due to their youth or specific environmental constraints.

These soils are heavily influenced by local factors such as water, wind, or topography and include:

4.1. Marsh Soils

Found in low-lying, waterlogged areas, these soils are often rich in organic matter but may require drainage for agricultural use.

4.2. Dune Soils

Derived from wind-blown sand deposits, these soils are typically loose and nutrient-poor, with limited vegetation.

4.3. Scree Soils

Formed from rock fragments on steep slopes, these soils are poorly developed and unsuitable for cultivation.

4.4.Alluvial Soils

Found along river valleys, these soils result from sediment deposition and are typically fertile, making them valuable for agriculture.

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