Alina Maciejewska | Łukasz Kuzak
Janusz Sobieraj | Dominik Metelski

Lignite

a natural source of organic matter and its impact on soil health

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Authors: Alina Maciejewska
Łukasz Kuzak
Janusz Sobieraj
Dominik Metelski

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Atena Editora
Ponta Grossa – Paraná – Brasil
Telefone: +55 (42) 3323-5493
www.atenaeditora.com.br
contato@atenaeditora.com.br

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ABSTRACT

ABSTRACT: Soil, a vital non-renewable resource, plays a crucial role in sustaining life on Earth. However, soil ionic imbalances, water eutrophication, and crop contamination pose significant challenges to agricultural systems. This study investigates the potential of lignite, an unconventional source of organic matter, as a sustainable alternative to high-dose mineral fertilizers. The research draws upon an extensive literature review and experimental data, considering both the chemistry of humus compounds in lignite and the formation of mineral-organic combinations that influence soil productive properties. The methodology involved analyzing the physical and chemical characteristics of lignite, including its types, genesis, global distribution, and chemical composition. Additionally, various lignite-based fertilizer blends, such as humic-mineral mixtures, nitrohumin-mineral blends, and humin-micronutrient mixtures, were evaluated for their efficacy in promoting soil health and crop yields. The results demonstrate the significant potential of lignite as a source of organic matter for soil amendment. Lignite-based fertilizers exhibited improved soil structure, enhanced nutrient availability, and increased water-holding capacity. Furthermore, the application of these fertilizers led to higher crop yields and reduced heavy metal uptake by plants, indicating their effectiveness in soil remediation and environmental protection. In conclusion, this study highlights the importance of exploring unconventional sources of organic matter, such as lignite, to address the challenges of soil degradation and ensure sustainable agricultural production. The findings underscore the need for adopting lignite-based fertilizers as part of an integrated soil management strategy, promoting soil health, crop productivity, and environmental conservation.

KEYWORDS: lignite; soil organic matter (SOM); humic acids; fulvic acids; soil health; soil fertility; sustainable agriculture; lignite-based fertilizers; soil remediation; environmental protection

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INTRODUCTION

The pursuit of sustainable agricultural practices has become a pressing concern due to the detrimental impacts of soil ionic imbalances, water eutrophication, and crop contamination. These challenges have prompted a shift towards reducing the reliance on high doses of mineral fertilizers and embracing organic or mineral-organic alternatives. This transition underscores the need to explore unconventional sources of organic matter that can ensure a steady increase in soil fertility while preserving ecological integrity and promoting the production of high-quality crops with desirable functional characteristics.

Among the emerging sources of organic matter, lignite, also known as brown coal, has garnered significant attention in recent years. Although the agricultural use of lignite can be traced back to the first half of the 20th century, its importance has escalated due to advancements in technology for obtaining various types of lignite-based fertilizers and the recognition of coal's specific sorption properties, which play a crucial role in water and plant protection.

This study, with over 750 bibliographic references, presents the findings of extensive research into the agricultural applications of lignite, drawing upon the available literature in the field and our own investigations. It delves into the chemistry of humus compounds present in lignite and explores hypotheses regarding the formation of various mineral-organic combinations that are pivotal in determining the productive properties of soils. The primary objective is to provide a comprehensive resource for students specializing in agricultural chemistry, soil science, and environmental protection, as well as valuable insights and practical assistance to agricultural workers, scientific research institutes, universities, and environmental engineering professionals, facilitating the adoption of sustainable practices and the preservation of soil health.

Soil organic matter (SOM) plays a vital role in maintaining soil fertility and ecosystem functions. It comprises a complex mixture of dead plant debris, roots, and organic matter from soil organisms, including dead organisms, animal feces, and microbial remains. This intricate composition is rich in carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and other essential elements, resulting from the decomposition and transformation of plant and soil organism-synthesized substances within the soil environment. The dynamic nature of soil organic carbon (SOC) highlights its pivotal role in ecosystem services and sustainability, with its continuous processing by microorganisms contributing significantly to the benefits derived from ecosystems. SOM influences soil physical, chemical, and biological properties, impacting soil structure, water retention, nutrient availability, microbial populations, and nutrient release, all of which are essential for ecosystem productivity and health.

Lignite is a valuable natural resource characterized by its unique chemical composition and sorption properties, making it an attractive option for agricultural applications and environmental protection. The interest in its agricultural use gained particular importance in recent years due to advances in technology for obtaining various types of lignite-based fertilizers and the recognition of coal's specific sorption properties, which are crucial for water and plant protection.

This study considers both the chemistry of humus compounds contained in lignite and hypotheses for the formation of various mineral-organic combinations that are essential in determining the productive properties of soils. By exploring the potential of lignite as an unconventional source of organic matter, this research contributes to the development of sustainable agricultural practices and the preservation of soil health and ecological integrity.

The first chapter, "Soil - a Natural Planetary Resource", explores the global distribution and diversity of soil structures across continents, looking at cultivated and degraded soils, highlighting the causes of soil degradation in Europe, identifying areas in need of remediation, and examining the unique soil structure of Poland.

The second chapter, "Soil Organic Matter", introduces the complex world of organic matter, a critical component underpinning soil health and fertility. It explores the sources, content, and functions of organic matter in soil formation, the ecological importance of humus, the process of humus formation, its effects on soil properties, buffering capacities, and its role in regulating metal ion solubility and pesticide binding. It also examines the natural determinants of organic matter content, rational management strategies, and the relationship between humus and the health of living organisms.

The third chapter, "Characteristics of Lignite", focuses on this natural resource as a source of organic matter, examining its types, origin, distribution, chemical composition, fertilizing value, the presence of humic acids, and its importance for the environment, including its ability to absorb pollutants and bind heavy metals.

The fourth chapter, "Lignite Fertilizer Blends", discusses various formulations and applications of lignite-based fertilizers, covering humic-mineral blends, nitro-humin-mineral blends, humin-micronutrient blends, delayed-action lignite blends, and lignite-organic-mineral blends, and their role in promoting sustainable agricultural production.

The fifth chapter, "Effects of Using Lignite in Field Crops", examines the practical applications of lignite in agriculture, investigating changes in soil properties resulting from varying lignite application rates, the effects on crop yields, and the ability of lignite organic matter to block heavy metals in soils, highlighting its potential for soil remediation and environmental protection.

By providing a holistic understanding of the multifaceted nature of soil, this publication aims to raise awareness and promote sustainable soil management strategies to ensure the long-term health and productivity of this invaluable resource, serving as a comprehensive resource for researchers, practitioners, and decision-makers, guiding us towards a future where soil is recognized, valued, and protected as the cornerstone of life on Earth.

SOIL - A NATURAL PLANETARY RESOURCE

Often undervalued, soil is one of our planet's most valuable resources. It is a highly important element of ecosystems, supporting life on Earth (Lal 2015). Soil plays a key role in agriculture (Kopittke et al. 2019), providing a substrate for plant crops (Smith et al. 2021), and, in turn, supplying nutrients and storing water (Silver et al. 2021). It also provides a habitat for numerous organisms, from microorganisms to invertebrates, which play an important role in the decomposition of organic matter and in maintaining a healthy ecological balance (Marumo 2003; Efeoğlu et al. 2022; Sangwan et al. 2020). Smith et al. (2021) delve into the essential functions of soil in supporting agriculture by highlighting how soils contribute to the growth and sustenance of plant crops. The authors discuss how soils act as a medium for plant growth, providing physical support for roots, facilitating nutrient uptake, and aiding in water retention. Additionally, the study explores the intricate relationship between soil properties and agricultural productivity, emphasizing the importance of soil health and fertility in ensuring successful crop cultivation. Smith et al.'s (2021) work underscores the fundamental role of soils in agriculture and their significance in sustaining food production through the provision of essential resources for plant growth. Kopittke et al. (2019) explore the critical relationship between soil health and agricultural intensification to ensure global food security. Their work emphasizes the importance of sustainable soil management practices in intensifying agriculture to meet the growing demands for food production while ensuring the long-term health and fertility of soils.

In this chapter, the focus will be on the role of soil as a natural resource and its importance for various aspects of life. The physical structure of soils, their chemical composition, and their biological diversity will be analyzed, as these factors affect the functioning of ecosystems and the availability of nutrients for plants (Nardi 2003; Beare et al. 1995; Lehmann et al. 2020; Jenny 1994). The examination of soil's multifaceted nature will shed light on its crucial role in sustaining life on Earth.

The formation of soil is a complex process resulting from the interplay of geological, climatic, biological, and anthropogenic factors over extended periods of centuries and millennia (Lamb and Rehm 2018). The physical, chemical, and biological properties of soil are shaped by various factors, including bedrock type, climate, topography, and the activities of soil organisms and humans (Lal 2004). Consequently, different regions of the planet exhibit unique soil types with distinct properties and varying abilities to support life, contingent upon the specific combination of these formative factors.

Soil is a dynamic and intricate entity shaped by a multitude of factors over extended periods. Beyond the initial formation processes, ongoing interactions continue to mold soil properties (Schulz et al. 2013). A crucial aspect influencing soil development is the presence and activity of soil microorganisms (Fierer, Jackson 2006). These microscopic organisms, including bacteria, fungi, and other microbes, play pivotal roles in nutrient cycling, organic matter decomposition, and soil structure formation (Schulz et al. 2013), contributing significantly to soil health and fertility, thereby impacting plant growth and ecosystem sustainability. Additionally, human activities have increasingly become a significant force in shaping soil properties (Santorufo et al. 2021). Anthropogenic influences, such as agriculture, urbanization, and industrial practices, can alter soil composition, structure, and fertility, leading to soil degradation or improvement, contingent upon the management practices employed (Kraamwinkel et al. 2021).

The physical structure of soils plays an essential role in their functioning (Meurer et al. 2020). Soil texture, comprising mineral particles, organic particles, and air, influences permeability, water retention capacity, and oxygen availability for plants (Sainju et al. 2022). Furthermore, soil structure determines the potential for plant rooting and the development of soil organisms that play a crucial role in the biological transformation and mineralization of organic matter (McCauley et al. 2005; Erktan, Sheu 2020). The study by Sainju et al. (2022) emphasizes the interconnectedness of soil physical properties, including texture, permeability, and structure, with other soil properties and agricultural productivity. It highlights how soil texture, permeability, and structure impact vital soil functions, such as water retention, oxygen availability, and the development of soil organisms crucial for biological processes and plant growth.

The research conducted by Erktan and Scheu (2020) investigates the physical structure of soil as a determinant and consequence of trophic interactions, elucidating how soil structure influences the interactions between soil organisms and the biological transformation of organic matter within the soil matrix. This study corroborates the vital role played by soil structure in determining the potential for plant rooting, the development of soil organisms, and the mineralization of organic matter, all of which are essential processes for soil functioning and plant growth. The findings underscore the intricate interplay between the physical structure of soil and the trophic dynamics within the soil ecosystem, highlighting the significance of this relationship in governing crucial soil processes and maintaining soil health.

The chemical composition of soils is crucial for facilitating plant uptake of essential nutrients (Morgan and Connolly 2013). Macronutrients such as nitrogen, phosphorus, and potassium, as well as micronutrients, are essential for plant growth and development, and their availability in the soil depends on a multitude of factors, including soil pH, organic matter content, and chemical and biological processes within the soil matrix (Morgan and Connolly 2013). Consequently, soil plays a major role in providing the requisite conditions for healthy plant growth and agricultural yields, thereby impacting human health (Johnson 2021). Morgan and Connolly (2013) discuss the significance of macronutrients like nitrogen, phosphorus, magnesium, and potassium, as well as the role of soil in nutrient availability for plant growth and development. Johnson (2021) emphasizes the essential nature of nutrients for plant functions, the distinction between macronutrients and micronutrients, and the importance of soil testing to determine nutrient requirements. These studies provide valuable insights into the essential nutrients required by plants, the impact of soil conditions on nutrient availability, and the critical role of soil in fostering healthy plant growth, agricultural productivity, and ultimately, human health.

Soil biodiversity is also crucial for ecosystem functioning (Brussaard 1997; Brussaard 2021). Micro-organisms, protozoa, nematodes, soil insects, and other soil organisms contribute to the decomposition of organic matter, the mineralization of nutrients, the improvement of soil structure, and the maintenance of biological balance. The growth of soil organism populations is linked to the presence of sufficient organic matter and favorable environmental conditions. Briones (2018) highlights the crucial role of soil fauna in litter decomposition, nutrient cycling, and promoting plant growth, which are essential aspects of ecosystem functioning. In the study by Brussaard (1997), the significance of soil organisms in high-input agricultural systems and the importance of soil biodiversity for ecosystem processes are discussed, emphasizing the diversity of soil organisms and its impact on ecosystem functioning. Liu et al. (2024) delve into the significance of cooperation among soil organisms in processes like organic matter decomposition, highlighting the essential role of soil biodiversity in maintaining soil health and ecosystem balance.

The subsequent sections of this chapter will consider different aspects of soil, focusing on soil structure in various regions of the world, including the soil structure present in Poland. Furthermore, an examination of the functions of soil in the ecosystem, such as water storage, chemical filtration, nutrient processing, and the impact of soil on climate change, will be undertaken. Developing a comprehensive understanding of these issues is paramount for soil conservation and the sustainable management of this valuable resource, which holds fundamental importance for future generations. The exploration of soil's multifaceted nature and its intricate role in ecological processes is essential for informing strategies aimed at preserving and optimizing this vital component of the Earth's systems.

1.1. SOIL STRUCTURE AROUND THE WORLD

Soils exhibit a high degree of structural diversity across the globe. This varying nature of soil structure can be attributed to numerous factors, such as the type of bedrock, climatic conditions, erosional processes, the activities of soil organisms, and the temporal scale over which the soils have formed (Berezin 1995). The study by the Royal Society (2024) synthesizes evidence on soil structure and its associated benefits, highlighting the relationship between soil structure and water and gas permeability, which are influenced by factors like soil organisms, climate, and land management practices, thereby contributing to the diversity of soil structures worldwide. Anderson (2023) discusses the importance of soil structure, the factors influencing aggregation, and the impact of biological activity, wetting/drying cycles, and other processes on soil structure development, which collectively contribute to the diverse range of soil structures observed globally. These scientific sources provide insights into the complexity and diversity of soil structures worldwide, shedding light on the various factors, including bedrock type, climate, erosional processes, soil organisms, and time, that contribute to the unique structural characteristics of soils across different regions.

The basic components of soil are minerals, humus, air, water, and soil organisms (Keefer 2000). Minerals form the soil skeleton and are derived from the breakdown of bedrock. These can include quartz, feldspar, argillaceous clay minerals, and other minerals that vary depending on the geographical area. The proportions of these minerals affect the soil texture, which determines the size of soil particles and their arrangement. Keefer (2000) discusses the composition of soil, emphasizing the presence of minerals, organic matter, air, and water, which collectively contribute to soil structure and fertility. Sparks (2024) provides insights into the importance of soil minerals in determining soil properties like texture, structure, and cation exchange capacity (CEC), underscoring how the type and proportions of minerals influence soil characteristics. Churchman and Lowe (2012) detail the role of soil minerals in soil fertility, highlighting their significance in nutrient storage and availability, and how weathering processes influence soil mineral composition and properties, which ultimately impact soil texture and structure. They provide strong scientific evidence supporting the role of soil minerals in soil fertility, nutrient storage and availability, and how weathering processes influence soil mineral composition, properties, texture, and structure.

The climate has a considerable impact on soil structure (Hsu, Dirmeyer 2023; Green et al. 2019). In humid and warm areas, biological and chemical processes, such as the decomposition of organic matter and chemical reactions, occur more intensively. Consequently, soils in such areas have a higher organic content and are more fertile. In dry areas, these processes occur more slowly, leading to a less developed soil structure and less organic matter. Hsu and Dirmeyer (2023) quantify how global warming affects soil moisture, highlighting the impact of climate change on soil conditions and the potential dehydration of soils, which can influence soil structure and organic content. More specifically, Hsu and Dirmeyer (2023) examine how increasing CO2 levels are causing shifts in soil moisture (SM) regimes globally. They find that under global warming, the range of SM extends into unprecedented coupling regimes in many locations. They found that: solely wet regime areas decline globally by 15.9%, transitional regimes emerge in currently humid areas of the tropics and high latitudes, and many semiarid regions spend more days in the transitional regime and fewer in the dry regime. These changes imply that a larger fraction of the world will evolve to experience multiple gears of land-atmosphere coupling, with the strongly coupled transitional regime expanding the most. This could amplify future climate sensitivity to land-atmosphere feedbacks and land management. Furthermore, Green et al. (2019) emphasize the significant influence of soil moisture on terrestrial carbon uptake, indicating how changes in soil moisture levels, driven by climate change, can impact soil structure, organic matter content, and the ability of land to store carbon. These studies provide insights into how climate variations affect soil structure, organic content, and fertility in different climatic regions, supporting the statement that humid and warm areas tend to have higher organic content and fertility due to more intensive biological and chemical processes compared to dry regions.

Soil organisms also play an important role in creating soil structure. Micro-organisms, fungi, protozoa, nematodes, worms and many other soil organisms contribute to the decomposition of organic matter, mixing and formation of soil aggregates (Lehmann et al. 2017; Guhra et al. 2022). Soil aggregates are groups of soil particles that are linked together as larger structures. They create a porous soil structure that facilitates water flow, air and plant root access and nutrient retention. The study by Lehmann et al. (2017) provides evidence of the positive effect of soil biota on soil aggregation, emphasizing the importance of bacteria and fungi in this process. Another relevant source is the article by Guhra et al. (2022) which discusses the role of soil organisms in aggregation due to bioturbation, organic matter decomposition, and excretion of organic matter.

Understanding the structure of the globe's soils is vitally important to many disciplines. In agriculture, knowledge of soil structure is essential for optimising cultivation practices, crop selection and fertilisation. In ecology, soil structure influences the distribution and interactions of organisms in soil ecosystems. In environmental protection, the identification of soil structure helps to plan measures to protect the soil from degradation and erosion. In addition, soil structure research is important with regard to global challenges such as climate change, given the role of soil in the carbon cycle and water retention. Fortuna (2012) addresses the importance of understanding soil structure across various disciplines, aligning with the statement provided. In the context of agriculture, the author delves into how knowledge of soil structure is crucial for optimizing cultivation practices, crop selection, and fertilization. It discusses how soil organisms, as part of the soil biota, contribute to soil health, nutrient cycling, and overall agricultural productivity by influencing soil structure. Furthermore, in the realm of ecology, the publication explores how soil structure impacts the distribution and interactions of organisms within soil ecosystems. It highlights the role of soil biota in shaping ecological processes, nutrient cycling, and biodiversity within soils, emphasizing the interconnectedness between soil structure and ecosystem dynamics. Regarding environmental protection, Fortuna (2012) emphasizes the significance of identifying soil structure to plan measures aimed at safeguarding soil from degradation and erosion. It discusses how maintaining healthy soil structure is essential for preserving ecosystem services, biodiversity, and soil fertility, thereby contributing to environmental conservation efforts. Lastly, concerning global challenges like climate change, the publication underscores the role of soil in the carbon cycle and water retention. It discusses how soil structure research is pivotal in understanding how soils sequester carbon, regulate greenhouse gas emissions, and influence water availability, thereby highlighting the importance of soil management practices in mitigating climate change effects. Overall, Fortuna's (2012) study provides insights into how soil biota and soil structure are intertwined, impacting agriculture, ecology, environmental protection, and global challenges like climate change, aligning with the multifaceted importance of soil structure across various disciplines as outlined in the statement. Bradford et al. (2019) address the importance of understanding soil structure across various disciplines. The authors discuss how knowledge of soil structure is crucial for optimizing cultivation practices, crop selection, and fertilization to enhance agricultural productivity. They delve into how soil structure influences the distribution and interactions of organisms in soil ecosystems, which is vital in ecology for understanding biodiversity and ecosystem functioning. Moreover, Bradford et al. (2019) explore the significance of soil structure in environmental protection by discussing how identifying soil structure aids in planning measures to protect soil from degradation and erosion. This aspect is crucial for maintaining soil health and ecosystem stability. Additionally, the publication touches upon the role of soil structure research in addressing global challenges like climate change. Soil plays a pivotal role in the carbon cycle and water retention, which are essential components in mitigating climate change impacts. Understanding soil structure is fundamental for managing soil as a carbon sink and regulating water resources, contributing to climate change mitigation efforts. Ghezzehei (2012) addresses the importance of understanding soil structure across various disciplines. In agriculture, knowledge of soil structure is crucial for optimizing cultivation practices, crop selection, and fertilization. This is because soil structure directly impacts factors like root growth, water infiltration, and nutrient availability, all of which are vital for successful crop production. In ecology, soil structure influences the distribution and interactions of organisms within soil ecosystems. Variations in soil structure can affect microbial communities, plant root systems, and overall biodiversity in the soil environment, highlighting the significance of understanding soil structure for ecological studies. Moreover, in terms of environmental protection, identifying soil structure is essential for planning measures to safeguard soil from degradation and erosion. Soil structure influences soil stability, erosion susceptibility, and water movement, making it a critical factor in soil conservation efforts. Lastly, soil structure research is crucial for addressing global challenges like climate change due to the role of soil in the carbon cycle and water retention. Understanding soil structure helps in managing carbon sequestration, water availability, and overall soil health, which are key components in mitigating climate change impacts and adapting to environmental changes. Therefore, Ghezzehei's (2012) study contributes to the broader understanding of soil structure and its implications across agriculture, ecology, environmental protection, and global challenges like climate change, emphasizing the multidisciplinary importance of soil structure research.

In later sections of this chapter, we will also discuss the functions of soil in the ecosystem, highlighting its role in water retention, filtration, providing nutrients for plants and as a habitat for organisms. In addition, we will look at the impact of soil on climate change, especially in the context of the role of soil in the carbon cycle and greenhouse gas emissions.

1.1.1 Distribution of soils across the continents

The distribution of soils across the continents is highly uneven and influenced by a variety of physical and human factors. Fertile, productive soils tend to be found in areas with moderate climates, adequate rainfall, and low-lying regions like river floodplains and deltas where nutrient-rich sediment accumulates. In contrast, poor quality soils are more common in very cold, dry, or wet regions that inhibit soil formation. For example, the tundra regions of northern North America and Eurasia have permafrost that limits soil development. Soil quality is also affected by human activities, as the overuse of fertilizers can lead to soil contamination and erosion (FAO 2024). Overall, the global distribution of soils reflects the complex interplay of natural processes and human impacts across the continents.

Here is some general information on the distribution of soils across the continents (Figure 1):

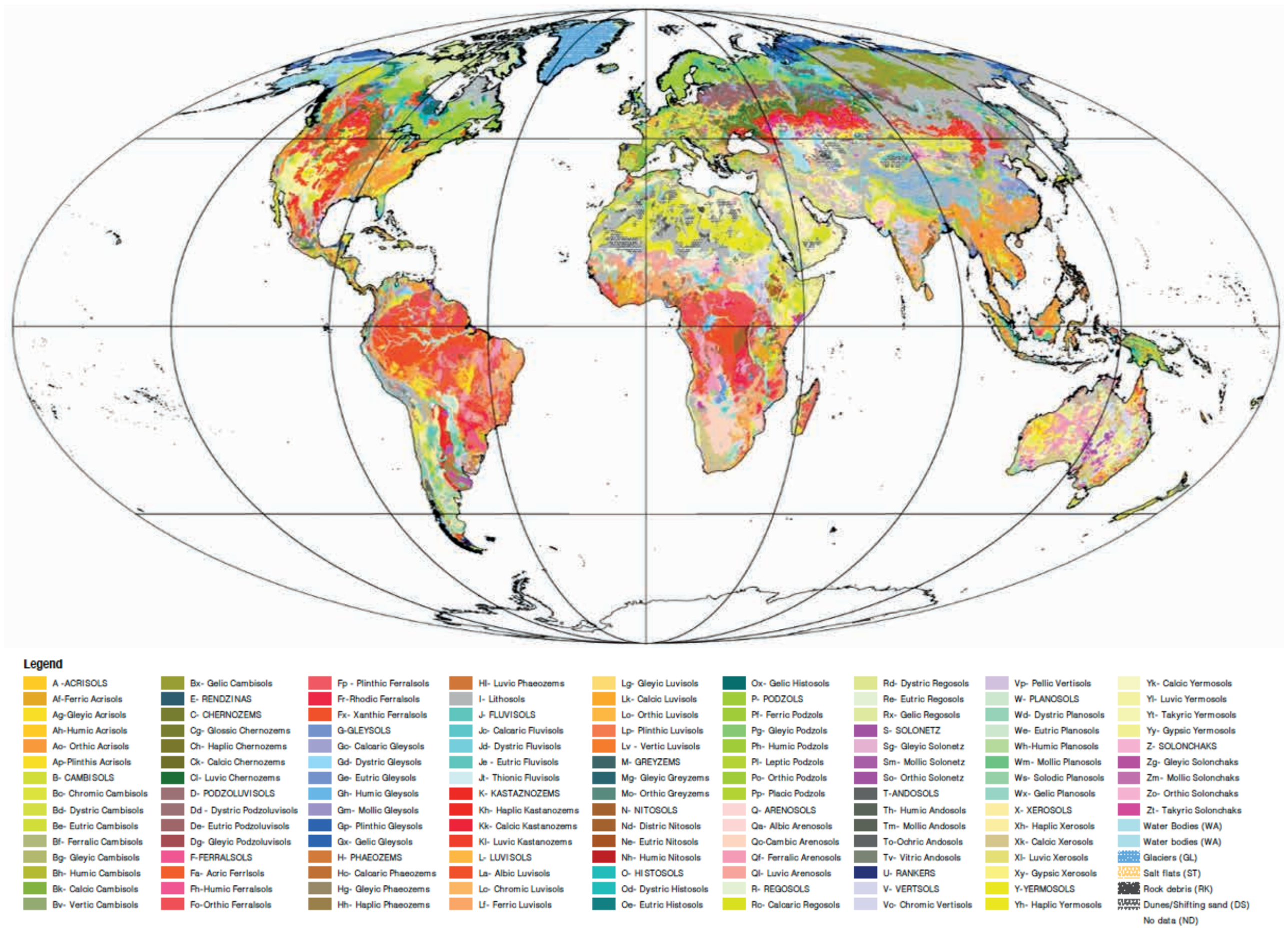

Figure 1. Digital Soil Map of the World (FAO 2024).

1.1.1.1. Spatial Distribution of Soils Across Africa

> *- Africa is home to a wide range of soils, with its varied geology and climate.*
> *- Northern Africa is dominated by desert soils, such as sandy soils and solonchaks.*
> *- The red ferralitic soils of the savannah and tropical forest zones of central and western Africa are poor in nutrients.*
> *- In southern Africa, especially South Africa, there are areas with fertile red soils that are beneficial for agriculture.*

Soil Atlas of Africa and its associated Soil Map

The Soil Atlas of Africa is a collaborative initiative of the European Union, the African Union, and the Food and Agriculture Organization of the United Nations to support and encourage the sustainable use of soil resources in Africa (Jones et al. 2013). It aims to raise awareness of the need for improved protection and sustainable management of soil resources in Africa, and builds on the considerable knowledge on soils in Africa amassed through the efforts of many individuals and organizations.

It should be noted that more than 60% of the soil types are hot, dry or immature soil complexes: Arenosols (22%), Leptosols (17%), Cambisols (11%), Kalcisols (6%), Regosols (2%) and Solonchaks (2%) [FAO 2024]. Then, there are tropical or subtropical soils, accounting for approximately 20%: Ferralsole (10%), Plintosole (5%), Lixisole (4%) and Nitisole (2%). A substantial area (6%) is covered by a further 16 reference groups, which cover less than 1% of Africa's land mass. This shows that a significant number of soil types are related to local soil-forming factors, such as volcanic activity, gypsum or silica accumulation, water saturation, etc.

Hot, dry or immature soils

Arenosols are formed by the weathering of quartz-rich parent material or in recently deposited sands, e.g. dunes in deserts and beaches (Baćmaga et al. 2021). These are some of the most extensive soil types in the world and are the most prevalent in Africa. The Kalahari sands are the largest sand accumulation on Earth (Daniell, van Tonder 2023). Soil formation is often limited by low levels of weathering. If vegetation has not developed, they may be susceptible to wind erosion. Once vegetated, there is an accumulation of organic matter, bands of clay or the formation of humus-clay complexes.

Leptosols are shallow soils on hard rocks, highly pebbled material or strongly calcareous sediments (Nachtergaele 2010). Due to limited pedogenic development, leptosols have a poor soil structure. Leptosols are found throughout Africa, especially in mountainous and desert regions where hard rocks are exposed or close to the surface and the physical breakdown of rocks as a result of freeze/thaw or heating/cooling cycles is the main soil-forming process.

Cambisols are a new soil type, only partly developed due to their young age. In general, they show only minor signs of soil-forming processes taking place, usually manifested by changes in colour, structure formation or the presence of clay minerals (Chesworth et al. 2008). They are widespread throughout Africa and can have different characteristics depending on the nature of the parent material, climate and terrain.

Calcisols are found in many parts of Africa, especially where the climate is dry enough to allow calcium carbonate to accumulate in the soil (Chesworth et al. 2008). They are formed by the leaching of carbonates from the topsoil, which precipitate out when the subsoil becomes saturated, from carbonate-rich water moving through the soil, or by the evaporation of water that leaves dissolved carbonates. Precipitated calcium carbonate can fill pores in the soil, thus acting as a cementing agent, and form a hard, solid layer (calcite) that is impenetrable to plant roots.

Regosols are poorly developed mineral soils with unconsolidated material of medium-to-fine texture (Harper 1957). Regosols show only slight signs of soil development — some accumulation of organic matter forming a slightly darker topsoil, which is often the only evidence of soil formation. Factors limiting soil development include low temperatures, prolonged dryness, parent material properties and erosion. Regosols are widespread in erosional areas, such as mountains or deserts, where soil formation is generally absent.

Solonchaks are high-alkaline soils. They are characterised by a dense, clay-rich subsoil containing high amounts of exchangeable sodium and a distinctive columnar structure (Gupta 2008). Sodium is able to disperse clay particles and organic matter in the topsoil, which are then washed away deep into the soil. The large pores are filled with clay and structural elements coated with organic coatings. Solonchaks are usually associated with flat areas in climates with hot, dry summers or with ancient coastal sediments that contain high salt content.

Tropical or subtropical soils

Ferralsols are highly weathered soils with low nutrient retention. They are widely distributed in central, eastern and southern Africa. Associated mainly with very old (Tertiary) land surfaces, these are heavily washed soils that have lost almost all their mineral content over time (Bougma 2022). As a result, they are dominated by stable products such as aluminium oxides, iron oxides and kaolinite, which give ferralsols their intense red and yellow colours. Calcium and magnesium levels are very low. The binding of particles by iron oxides gives the impression of a sandy or silty structure (so-called pseudo-sand).

Plintosols show accumulation of iron (and manganese) in the subsoil in the form of large **mottles** or concretions. This iron-rich layer develops mainly under the influence of fluctuating groundwater (Singh, Gilkes 1996). Below ground it is soft, but once exposed to air and sunlight it hardens irreversibly and is often referred to as ironstone (Singh, Gilkes

1996; Justham 2008; Salama et al. 2014). Once brought to the surface by erosion, a hard layer of ironstone forms a cap that protects the area from further erosion (Singh, Gilkes 1996).

Lixisols are slightly acidic soils that show a marked increase in clay content with depth (Dengiz et al. 2018). The clay is mainly kaolinite with limited nutrient retention capacity (Ebelhar et al. 2008) and is mostly found fin the dry savannah region with low biomass production (Malinova et al. 2021; Dengiz et al. 2018). Lixisols do not contain much organic matter and do not have a well-developed soil structure. Intense rainfall is capable of destroying any soil structure present, making it vulnerable to erosion. The flow of water can then erode the topsoil, that is, the most fertile part. Wind erosion can also be a problem, as loose soil particles on the surface can easily be blown away.

Nitisols are mainly formed from basic iron-rich rocks such as basalt (Arbestain et al. 2008). Their main characteristics are their dark red colour and well-developed structure with a nutty appearance and glossy surface. The content of active iron (i.e. amorphous iron oxides and hydroxides) is high, forcing soil particles to bind strongly and form nut-shaped aggregates. The shiny surfaces are a mixture of clay and iron. Most nitisols are dominated by kaolinitic clay (Elias, Agegnehu 2020). They are common in East Africa, but also in many other parts of Africa.

1.1.1.2. Spatial Distribution of Soils Across North America

- There are many different soil types in North America, given its varied climate and geology.
- Podzolic soils are the most prevalent type in Canada and the northern regions of the USA. These are well drained and contain a large amount of organic matter.
- In the central part of the USA, in the Great Plains area, there are black prairie soils (Mollisols), which are very fertile and beneficial for agriculture.
- Brown soils, which are rich in nutrients, are found on the west coast of the USA, especially in California.

Britannica – North America, Land

Soils of grasslands, deserts and tundra

Soils in this group cover an extensive area of North America and are usually found in drier or cooler regions of the continent where trees are not common. The most common soils are Mollisole (21.5%), Wertisole (12.3%), Ultisole (9.2%), Gelisole (8.7%) and Aridisole (8.3%).

Mollisols are found in open parklands, the grass prairies of the Great Plains and moist prairies of the western Central Plains (Liu et al. 2012). Unlike the forest soils mentioned above, these soils formed under grassland vegetation and were strongly influenced by tightly bound roots in a dense turf of dense grasses. The roots eventually decompose underground, turning into humus and giving the mollisols a dark brown or black colour. Due to the short rainy period from April to mid-July, followed by significant evaporation during the dry, sunny summer, a shallow washout occurs, going down to the horizon where the upward movement of water caused by evaporation from the surface has brought salts, especially lime (Liu et al. 2012). Extremely fertile and pH-neutral, mollisols make up most of the Wheat Belt in the central Great Plains and the productive Palouse area of eastern Washington where wheat is grown. Further east, where rainfall is higher, the corn belt in Illinois and Iowa is also centred on mollisols.

Vertisols form in materials with a high clay content where there are distinct wet and dry pores; they are distinguished by large, deep cracks that form on the surface during dry periods when the clays shrink and dry out (Teshale 2023). These soils are limited in North America to small areas of Mexico and Texas (University of Idaho 2024). With regard to irrigation, vertisols are very efficient for growing cotton and sweetcorn and for use as pasture (Teshale 2023). However, the use of these soils as foundations for houses and other structures may be problematic as they swell when wet and shrink when dry.

Ultisols are soils that have developed in humid areas and are intensely weathered (University of Idaho 2024). They usually contain subsoil with a considerable amount of translocated clay and are relatively acidic. Most of the nutrients are concentrated within a few centimetres of the soil surface, and although these soils do not tend to be the most fertile, they can become productive with the addition of fertiliser and lime (Oktari et al. 2021). Ultisols make up around 8% of the glacier-free land area.

Aridisols Characterised by the arid climate of the intermountain basins of the United States, most of the Mexican Plateau and the southwestern Pacific coast, arid soils occur where vegetation is scarce, and thus, where little humus has formed on the surface (University of Idaho 2024). Leaching is infrequent and practically ineffective; strong evaporation leads to the upward movement of alkaline salts by capillary action, which often leaves a crust of white lime salt crystals on the surface. Aridisols are too rich in calcium, and often in sodium, to be fertile unless they are intensively irrigated and the salts are removed. A study by Ogura et al. (2016) found that incorporating torrefied biomass into an aridisol from Botswana improved its physical, chemical and biological properties. The torrefied biomass enhanced water retention, mineral availability for plants, and initial plant growth (Ogura et al. 2016). It also altered the soil metabolic and microbial dynamics. However, without irrigation and removal of accumulated salts, aridisols are not suitable for agriculture due to their high alkalinity and salinity (University of Idaho 2024).

Gelisols, recognised as a separate soil type in the late 1990s, are soils found in very cold climates (Dudeja 2011). They contain permafrost within 2 metres of the surface (University of Idaho 2024). The active (seasonal thaw) gelisol layer and the upper part of the permafrost contain materials that show signs of cryoturbation (mixing of materials from different horizons due to soil freezing and thawing; also known as frost compaction) or ice segregation (Dudeja 2011). These soils are geographically restricted to the polar regions, where tundra vegetation is widespread, and to localised areas at high altitude. Extremely cold landscapes where gelisols occur result in dramatically slowed soil processes and high sensitivity to human contact. Today, most gelisol areas are covered with native vegetation (University of Idaho 2024).

Other soils

The three soil types are distinguished by their relative youthfulness - i.e. a greater affinity for the parent minerals than for the vegetation associated with them - and can be found scattered throughout most vegetation environments. These include Entisols (12.3%), Inceptisols (9.7%) and Histosols.

Entisols are the youngest and least developed soils. These soils strongly resemble their geological parent materials because there has not been enough time to turn these materials into soils with strongly developed horizons (University of Idaho 2024). Disturbed landscapes also have soils classified as entisols, such as the many square miles of land occupied by highways and urban centres in North America. Natural landscapes, such as the Sand Hills in Nebraska, are also areas of entisols. These soils also occur on steep mountain slopes, where long-term erosion processes have kept pace with soil-forming processes and deep soils cannot form. Since disturbed or eroded sites or recently deposited materials, such as river alluvium, are common in all landscapes, entisols are widely dispersed throughout North America.

Inceptisols are slightly more weathered and developed than entisols; like entisols, inceptisols are not clearly associated with any particular climatic regime, but are widely distributed across the continent (Tubana et al. 2016; USDA 1999). They are common in the tundra landscapes of northern Canada and in the high elevations of the Cordillera and form the fertile soils of the Pacific Northwest and the coasts of British Columbia and Alaska. Many soils formed from acid glacial till in the New England Mountains are also inceptive soils.

Histosols - saturated with water for many months of the year, histosols are nothing more than deep accumulations of organic materials (SSSA 2024). They are particularly common under the coniferous forests and swamps of the Great Lakes area and Canada, where geologically recent glaciation has left many areas of standing water or shallow lakes (Volungevicius, Amaleviciute-Volunge 2023). The cool climate of these areas also limits the decomposition of wood fragments, grasses, sedges and mosses that may have accumulated in damp areas. Histosols are also known as peat and muck soils (SSSA 2024). In some areas, peat is extracted and used as a soil additive.

1.1.1.3. Spatial Distribution of Soils Across South America

- There are a wide range of soil types in South America, depending on the latitude and differences in climate.
- In the Amazon and Amazon basin regions, red and yellow laterite soils predominate.
- In the Andes, at altitudes above 3,000 metres, there are mountain andosol soils that are rich in minerals and well-drained.
- The Pampa zone of Argentina, Uruguay and Brazil have fertile black soils, known as chernozem soils, which are highly favourable for agriculture.

Soil Atlas of Latin America and the Caribbean

South America has a wide range of soil types and all WRB reference groups can be found there. It is important to note that approximately 30% of LAC soils are tropical or subtropical in nature: Ferralsole (17%), Acrisole (12%), Lixisole (2%) and Plintosole (1%). Other groups well represented on the continent include: Kambisole (9%), Regosole (6%), Feoziemy (6%), Glejsole (5%), Arenosole (5%), Louvisole (4%), Solonchaks (3%) and Kalcisole (2%) [ECJRC 2011].

Tropical or subtropical soils

Ferralsoles are highly weathered soils with low nutrient retention, widespread in Latin America and often associated with acresols (ECJRC 2011; Riquetti et al. 2023). They are common in areas with abundant rainfall and old parent materials (Tertiary period). These soils are subjected to strong weathering processes that lead to the loss of most weathering minerals and leaching of large amounts of silica and base cations (Hardy 1942). For this reason, they are dominated by stable compounds such as kaolinite, as well as aluminium and iron oxides. The latter have an intense, characteristic colour (red and yellow).

Acrisols are acidic soils dominated by kaolinite with a level of clay accumulation in the subsoil (Dowuona et al. 2012; Mathian et al. 2020; Ouyang et al. 2021). They are very common in the southern part of the Amazon basin. They are nutrient-poor and require a significant application of fertiliser or other measures to achieve satisfactory crops (Ouyang et al. 2021). The high kaolinite content and advanced weathering of Acrisols contribute to their low fertility and need for amendments to support crop production.

Other soils

Cambisols are highly weathered soils with low nutrient retention that show signs of soil formation through colour changes, removal of carbonate or gypsum, or formation of clay minerals. These soils cover extensive areas in a wide range of landscapes (both plains and mountains) and climates, with different vegetation cover (Tengberg 1998).

Regosols are soils consisting of soft material and poorly developed. More specifically, they are characterized by shallow, medium- to fine-textured, unconsolidated parent material and lack of significant soil horizon formation due to dry or cold climatic conditions (Meek et al.

2008). They occur mainly in polar and desert regions, occupying about 2% of the continental land area on Earth. Regosols are often found under their original natural vegetation or under limited dryland cropping. The study on soil gross nitrogen transformations in forestland and cropland of Regosols in the Sichuan Basin of China found that Regosols have low organic matter content (Ren et al. 2021). Another study on the influence of soil type and use on organic carbon distribution showed that Regosols have the lowest organic carbon content compared to Fluvisols (Marín-Sanleandro et al. 2023). They are not used for agricultural production and, as with leptosols, much of this soil type is used for extensive grazing. In other cases, the natural vegetation is preserved or the slopes are reforested. In general, they are only useful for agriculture in cool and humid climates.

Phaeozems are characterised by a thick, dark, humus-rich, mineral surface horizon. They are mainly found in regions with moderate humidity. Their relatively high humidity prevents the accumulation of secondary carbonates or soluble salts. Due to the high humus content and the calcium ions that bind to the soil particles, pheozems have a highly permeable and well-compacted structure. These are fertile soils found in South American pampas and high altitude forests in the tropics.

Gleysols are mainly found in low-lying areas or depressions where groundwater approaches the surface and the soil is saturated for long periods. The lower part shows reduced iron and bluish-grey colours. From below, water rises by capillary action and evaporates from the surface of the aggregates, where the iron is oxidised by the oxygen in the air, giving rise to brown, red and yellow mottling. Gleissols are found in the humid tropics (Guyana Highlands, Amazon and humid Andean regions).

Arenosols are some of the most extensive soil types in the world. These soils are sandy and easily erodible, with low available water content and low nutrient retention (Kazlauskaite-Jadzevice et al. 2023). Two groups can be distinguished according to their genesis: recent sand deposits (deserts, beaches and dunes) and quartz-rich sands that accumulate residually through advanced weathering of other minerals, usually in humid tropical climates. In Latin America, these soils are particularly suitable for growing coconut, cassava and maize. In semi-arid regions, they can only maintain extensive grazing with low yields.

Luvisols are slightly acidic soils with a clay-like subsoil and high nutrient retention (Ejigu et al. 2023). They show a marked variation in texture in their profile, as a result of the movement of clay in the upper part of these soils to the lower part. They are characterised by their high base saturation and high alumina content. They occur mainly in young landscapes that experience periods of drought in Mexico, Cuba, Dominican Republic, Nicaragua, Ecuador, Peru, Venezuela, Brazil, Uruguay and Argentina. The soils in this group, with the exception of some types, are suitable for a wide range of uses. Lavkulich and Arocena (2011) provide more details on the characteristics of Luvisols, noting that they tend to accumulate swelling clays in drier climates and that most Luvisols are well-suited for agriculture, with a few exceptions. The paper also highlights the need for proper management to maintain soil structure and prevent erosion in certain Luvisol types.

1.1.1.4. Spatial Distribution of Soils Across Asia

- Asia is the largest continent and is home to a wide range of soils, given differences in climate, topography and geology.
- Glacial and tundra soils are found in polar and mountainous areas.
- Red and yellow ferralite soils are found in the equatorial zone of Southeast Asia and the Indian Peninsula.
- Chestnut soils, which are rich in organic matter, are found in steppe regions in eastern Asia, such as Mongolia and Kazakhstan.
- In Central Asia, in the Tarim Basin and Kashgar Basin regions, there are solonchaks and desert salt soils.

Soil Atlas of Asia

Asia's soil resources are diverse, reflecting the extremely varied combinations of climatic conditions and parent materials on the continent. Its soils range from cryosols in the north to extensive peatlands in south-east Asia. The Fluvisols lie along the main waterways of western, southern and eastern Asia and are considered the birthplaces of agriculture, while the volcanic Andodols mark the Pacific Ring of Fire. Asia contains some of the most fertile soils on the planet. However, many soils are also inherently vulnerable because they are poor in nutrients and organic matter. A lack of water is also a major constraint with regard to their use in agriculture (Dou et al. 2022).

The main soil types found in Asia include Cambisols (18%), Leptosols (11%), Cryosols (8%), Kalcisols (7%), Arenosols (6%), Podzols (5%), Akrisols (4%), Fluvisols (4%), Chestosols (4%) and Gleysols (4%).

Cambisols are moderately developed soils due to their young age. They show only minor signs of soil-forming processes, usually through colour changes, structure formation or the presence of clay minerals. They are widespread throughout Asia and can have different characteristics depending on the nature of the parent material, climate and terrain (Cheng 2014).

Leptosols are shallow soils on hard rocks, extremely gravelly material or calcareous sediments (Ebelhar et al. 2008). Due to limited pedogenic development, leptosols have a poor soil structure. Leptosols tend to occur in mountainous and desert regions where the bedrock is exposed and physical rock disintegration caused by freeze/thaw or heating/cooling cycles is the main soil-forming process (Kimeklis et al. 2021).

Cryosols are soils found in cold regions with permafrost and/or cryoturbation. Cryosols develop in cold regions with permanently frozen ground (permafrost). In this soil type, water occurs mainly in the form of ice and cryogenic processes such as freeze-thaw cycles (Tarnocai, Bockheim 2011). Cryoturbation (vitiating), frost rippling, cryogenic sorting, ice cracking and segregation are the dominant soil-forming processes (Chen et al. 2003).

Calcisols are soils with a significant accumulation of calcium carbonate, usually found in dry areas (Chesworth et al. 2008; Cantú Silva et al. 2018). Calcisols are common throughout Asia, where the climate is dry enough to allow calcium carbonate to accumulate in the soil. They are formed by the leaching of carbonates from the topsoil, through water containing carbonates moving through the soil, or through the evaporation of water that leaves behind dissolved carbonates. Precipitated calcium carbonate can fill the pores in the soil, which acts as a cementing agent, forming a hard, solid layer that is impenetrable to plant roots (Akça 2018).

Arenosols are sandy soils with low water and nutrient retention (Gus-Stolarczyk et al. 2021). Arenosols are formed by in situ weathering of quartz-rich parent material or in recently deposited sands (e.g. dunes and beaches). These are some of the most extensive soil types in Asia. Soil formation is often interrupted by low rates of weathering. If vegetation has not developed on them, they may be susceptible to wind erosion. After vegetation, the accumulation of organic matter, bands of clay or the formation of humus-clay complexes may occur (Gus-Stolarczyk et al. 2021).

Podzols are acidic soils with a bleached horizon underlain by leached material (Stobbe 1961). The podzols have a distinctive ash-grey horizon that has been bleached by the loss of organic matter and iron oxides (Weber et al. 2017). This lies above a dark horizon of re-deposited humus accumulation and/or reddish iron compounds. It is usually found in quartz-rich sands in temperate zones with high rainfall, often under coniferous forests.

Acrisols are highly acidic soils (i.e. pH <7) with a subsoil enriched in clay and the ability to retain nutrients. They are dominated by low-load minerals such as kaolinite, with a subsoil horizon that shows clay accumulation (often with a corresponding lighter horizon above from which the clay has been removed) [Dahlgren et al. 2008; Ghartey et al. 2012]. They are quite common in Asia and are mainly found in more humid parts of the tropics and subtropics. They are usually associated with acidic bedrock (e.g. granite) and are nutrient-poor, thus requiring a significant application of fertiliser to achieve a satisfactory harvest (Dahlgren et al. 2008).

Fluvisols are young, soft soils found in lakes, deltas and tidal sediments, as well as all periodically flooded areas, such as floodplains, river fans, valleys, tidal marshes and mangroves (Telo da Gama et al. 2023). They show sediment build-up as a result of embedding by water. Their characteristics and fertility depend on the nature and sequence of the sediments, as well as the intervals between floods.

Kastanozems are soils with an organic-rich topsoil and carbonates in the subsoil (Aksoy et al. 2018). Chestnut lands have a deep, dark-coloured surface layer with a significant accumulation of organic matter, high base saturation (pH) and calcium carbonate accumulation in the subsoil. They thrive in the drier parts of shrubby grassland habitats where there is still sufficient biomass production to form an organic matter-rich surface layer and dry enough to facilitate the precipitation of carbonates or gypsum.

Gleysols are soils saturated with groundwater for a long time (Ahmad et al. 2020). Gleysols occur in low-lying areas or depressions where groundwater approaches the surface and the soil is waterlogged for long periods (saturated with water). The gleysols show characteristic reddish, brownish or yellowish colours in the upper part of the soil, where oxygen is present, combined with greyish/blue colours deeper in the soil where oxygen is absent (this condition is referred to as reduced).

1.1.1.5. Spatial Distribution of Soils Across Europe

Soil Atlas of Europe

Within Europe, the factors determining the distribution of soils are the continent's location in the northern hemisphere, the diverse climate and vegetation cover, the complex geological structure and relief and the highly developed coastline (Virto et al. 2014). Europe has soils from four climate-soil belts: polar, boreal, subboreal and subtropical. The main soil types found in Europe include: Albice (15%), Podzole (14%), Cambisole (12%), Chernozem (9%), Leptosole (9%), Louvisole (6%), Kalcisole (5%), Fluvisole (5%), Glejsole (5%), Histosole (5%), Feoziemy (3%).

Albeluvisols are acidic soils characterised by an accumulation of clay in the subsoil with an irregular or interrupted upper boundary and deep penetrations or 'tongues' of bleached soil material into the illuvial horizon (Szymański, Skiba 2007). Typical 'tongues' are usually the result of freezing and thawing processes under periglacial conditions and often show a polygonal network in horizontal cuts. Albice are mainly found in humid and cool temperate regions. They are dominant in north-eastern Europe.

Podzols are acidic soils with a podzolised horizon underlain by an accumulation of organic matter, aluminium and iron (Dymov et al. 2023). Under acidic conditions, aluminium, iron and organic compounds migrate from the soil surface down to the B horizon with percolating rainwater. Humic complexes are deposited in the accumulation (spodic) horizon, while the overlying soil is left as a strongly bleached albic horizon. Most **podzols** develop in moist, well-drained areas, especially in the boreal and temperate zones (Ilichev et al. 2021). They are found primarily in northern and central Europe.

Cambisols are soils that are only moderately developed due to their young age or rejuvenation of the soil material. These are young soils and pedogenic processes are evident in the development of colour and/or the formation of structure below the surface level (Petrova 2018). Cambisols are found in a wide variety of habitats across Europe and under many types of vegetation. They are commonly referred to as **brown soils**.

Chernozem are soils with a deep, dark surface horizon, rich in organic matter and secondary concentrations of calcium carbonate in the deeper horizons (Kabała 2019). These soils have a very dark brown or blackish surface horizon with a significant accumulation of organic matter, high pH and calcium carbonate deposits within 50 cm of the lower limit of the humus-rich horizon (Korsunova, Valova 2021). Chernozem show high biological activity and are usually found in steppe regions of the world, especially in Eastern Europe, Ukraine and Russia. Chernozem are among the most productive soil types in the world.

Leptosols are shallow soils over hard rock and consist of extremely gravelly or highly calcareous material (Lessovaia et al. 2008). They mainly occur in mountainous regions and in areas where the soil has eroded to the point where hard rock approaches the surface. Due to limited pedogenic development, leptosols do not have a complex structure and are found all around the world. Leptosols on limestone are called **Rêtes**, while those on acidic rocks such as granite are called **Rankers**.

Luvisols are soils with a subsurface clay horizon characterised by high activity, accumulation and high base saturation. Research indicates that Luvisols exhibit a distinct red-brown and/or yellow color due to the presence of pedogenic iron oxides, emphasizing the importance of these minerals in the soil's development (Kotroczó et al. 2023). Additionally, studies have shown that Luvisols have a higher clay content in the argic horizon compared to the eluvial horizon, with clay migration being a significant process in their formation (Piotrowska-Długosz et al. 2021). Furthermore, enzyme activity in Luvisols is highest in the topsoil layers and decreases with depth, influenced by the availability of carbon and nutrients (Grozav, Rogobete 2019). The biological activity and soil respiration in Luvisols are significantly impacted by the presence or absence of organic matter, highlighting the importance of organic inputs in maintaining soil productivity and enhancing soil biological activity (Jordanova 2016). Louvises show marked textural differences within the profile. The surface horizon is clay-depleted, while the subsurface 'argillic' horizon has accumulated clay. The wide range of parent materials and environmental conditions leads to a large diversity of soils in this reference soil group. They are found throughout Europe. Other names used for this soil type include **pseudoblitz** or **pseudobrown soil**.

Calcisols are soils with significant accumulation of secondary calcium carbonates, usually found in arid areas (Montpied et al. 2010; Manafi 2019). Calcisols are characterised by significant movement and accumulation of calcium carbonate in the soil profile (Khaled et al. 2023). Calcisols are common on calcareous parent material in regions with pronounced dry seasons, as well as in arid areas where carbonate-rich groundwater approaches the surface. Historically, calcareous soils were known as **desert soils**.

Fluvisols are young soils found in alluvial (floodplain), lake and marine sediments. Fluviosols are common in periodically flooded areas, such as alluvial plains, river fans, valleys and tidal marshes, on all continents and in all climate zones (Kanianska et al. 2022). Fluvisols show sediment stratification rather than pedogenic levels (Šimanský 2018). Their properties and fertility depend on the nature and sequence of the sediments and the length of the periods of soil formation after or between floods (Furtak et al. 2019). Common names for these soils include **alluvial and deluvial soils** and **fen soils**.

Gleysols are soils saturated with groundwater near the surface for a long time and are mostly found in lowland areas (Rits et al. 2016). Conditioned by excessive moisture at shallow depth, this soil type develops glial colour patterns consisting of reddish, brownish or yellowish colours on the surfaces of the pedicels or in the upper soil layers, combined with greyish/blueish colours inside the pedicels or deeper in the soil profile. The common name for these soils is **gley soils**.

Histosols are dark soils with a high accumulation of partially decomposed organic matter, usually developing in wet or cold conditions. Histosols consist mainly of organic soil material (Tisdall, Oades 1982). Histosols are known for their accumulation of organic carbon, with some estimates suggesting that they contain about 20% of the Earth's organic carbon (Duboc et al. 2014). This high organic matter content in Histosols plays a crucial role in their properties and functions within ecosystems (Santos et al. 2020). Histosols are rich in carbon and nitrogen reserves, which contribute to their fertility and ability to support plant growth (Santos et al., 2020). During development, the production of organic matter exceeds the rate of decomposition. This delays the latter, primarily as a result of low temperatures or anaerobic (low oxygen) conditions, which lead to a significant accumulation of partially decomposed organic matter. Histosols are mainly found in the boreal and subarctic regions of northern Europe and central Europe and are also known as peat soils and bog soils.

Phaeozems are soils with a deep, dark surface horizon rich in organic matter, with no secondary calcium carbonate concentration within a 1 m radius. Phaeozems are found in humid steppe regions (prairies) and are similar to chernozems and chestnuts, but are more intensely leached during the wet seasons. As a result, they have a dark, humus-rich surface horizon and no secondary carbonates in the upper metre of soil (Junior et al. 2022). The common name for this type of soil is **black earth**.

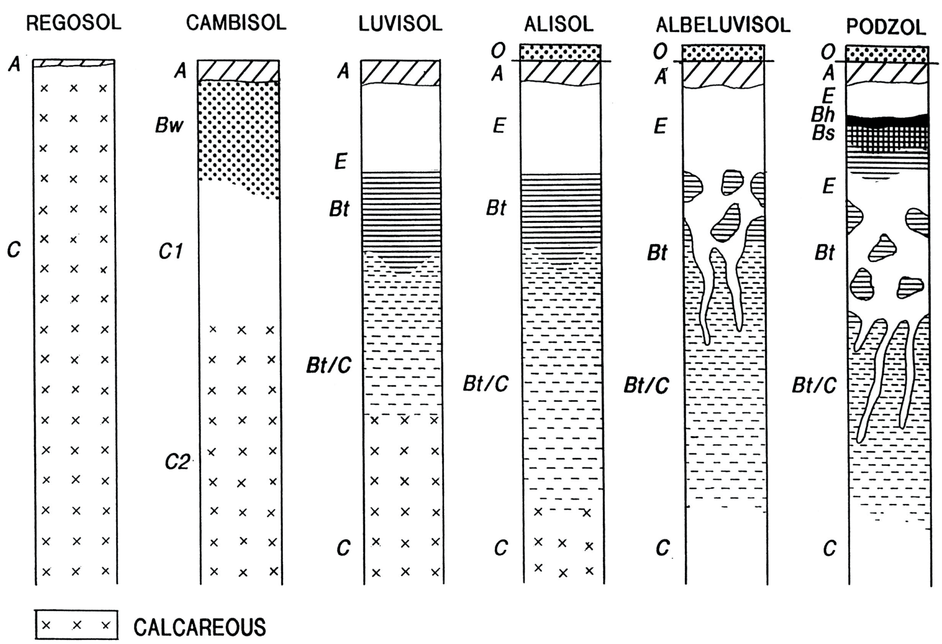

Figure 2. Soil profiles of the most important soil types in Europe (Jones et al. 2005).

1.1.1.6. Spatial Distribution of Soils Across Australia and Oceania

Britannica – Australia, Land

The composition and dynamics of continental soil patterns are closely linked to climatic factors, as indicated by various research studies. Soil microbial communities are influenced by climatic variables such as temperature and precipitation, which indirectly affect microbial community composition through factors like plant productivity and soil mineralogy (Baum et al. 2022). The diversity and composition of soil bacteria globally are significantly influenced by climatic features like temperature and soil factors such as pH and organic matter content, highlighting the importance of climate and soil properties in shaping soil bacterial diversity at a global scale (Baum et al. 2022).

The vulnerability of soil organic carbon to decomposition across Australia is shown to be influenced by climate, soil properties, and elevation, emphasizing the intricate relationship between continental soil patterns and climatic factors (Waldrop et al. 2017). Mineral or skeletal soils occur over much of dry Australia, containing virtually no organic matter and developing at shallow depth (Stanbery et al. 2023); they may consist only of a rough mantle of weathered rock. Gypsum is present in many desert clays and dry red earths, while the soils of semi-arid regions (where annual rainfall ranges from 8 to 15 inches [203 to 380 mm]) are also alkaline, with gypsum or lime (Doolette et al. 2016). The organic matter content of soils is low in the solonised (salt-enriched) brown soils and the grey and brown heavy textured soils common in these areas.

Australian dryland soils differ from global drylands, showing ancient weathered soil traits with lower pH, total N, available P, and higher C:N and C:P ratios, along with distinct microbial communities favoring specific phylotypes (Stanbery et al. 2023; Li et al. 2022). In arid and semi-arid ecosystems, the distribution of organic matter fractions varies across latitudinal gradients, with climate primarily influencing light fraction organic matter and soil physicochemical factors driving heavy fraction organic matter variation (Dörken et al. 2020). Moreover, the morpho-anatomical features of plants in arid environments, such as xerophytes with water-saving adaptations, contribute to their success in dry conditions (Unkovich et al. 2020).

Patterns of guilds, swells, and depressions in arid and semi-arid Australian regions are influenced by the alternate swelling and shrinking of clay soils after wetting and drying, particularly visible in areas with seasonal rainfall (Tarin Terrazas 2019). Regions with annual rainfall between 15 to 25 inches (380 to 635 mm) are more likely to have black earth, brown, and red-brown soils, while wetter areas exhibit mineral leaching as a prominent soil feature (Maisnam et al. 2023). The characteristic soil types in these regions include podzolic soils, sandy with abundant surface humus and acidic throughout, and humus soils in Alpine regions, characterized by surface peats over minerals (Filippi et al. 2018). These soil characteristics play a crucial role in shaping the ecosystems and vegetation composition in these arid and semi-arid environments, impacting the overall functioning and biodiversity of these regions.

These broad, climatically-driven soil patterns are compounded by local variations related to topography, groundwater conditions and parent materials. For example, red soils of one type (karstosems) are formed on the basalt outcrops so typical of eastern Australia, while those of a different composition (terra rossas and rendzinas) are formed on limestone substrates (Lucke et al. 2014). Furthermore, laterite and silcrete were formed in distant geological times, when conditions were very different from today (Ghosh, Guchhait 2020). Laterites, deep weathering profiles developed under tropical climates, serve as archives of past climates, forming in periods with very favorable conditions (Schmidt, Hiscock 2019). Silcrete, on the other hand, remains somewhat of a geological mystery, with various interpretations of its origins in different regions, including Australia (Taylor, Eggleton 2017). The silcrete formations in Australia, particularly in Eastern Australia, have been studied to understand long-term technological advancements, indicating shifts towards greater heat treatment frequencies over millennia, possibly due to lithic resource depletion and political barriers (Ghosh, Guchhait 2020). Additionally, similarities between laterites in India and Australia suggest a shared history of lateritization events due to the movement of continents to tropical latitudes over millions of years (Heller et al. 2023). Laterite is represented in every state, including Tasmania, although it does not currently form anywhere in Australia, while siliceous material is restricted to dry Australia and parts of sub-humid Western Australia, South Australia and Queensland. Most of Australia's silicification is thought to have occurred during the Neogene (Newberry 2005).

It is worth noting that the above information is general and the distribution of soils can be more complex, taking into account local conditions and micro-regions.

1.1.2 Cultivated soils by continent

Agricultural land and soils used for farming worldwide cover approximately 5 billion hectares, accounting for 38% of the world's total land area (FAO 2022). About a third of this is used as arable fields, while the remaining two-thirds is grassland and pasture used for livestock grazing. Approximately 10% of the arable field area is used for permanent fruit trees, oil palm plantations and cocoa plantations, and only 21% is equipped with irrigation systems.

As the world's population continues to grow, food demand is also steadily increasing. However, the amount of land dedicated to agriculture worldwide continues to decrease. In other words, as the global population expands, the demand for food rises while agricultural land availability diminishes. Studies show that agricultural technological progress has been crucial in saving land globally, with a preferred estimate indicating that without observed total factor productivity (TFP) growth, an additional 173 million hectares of land would have been required to meet food demand from 1991 to 2010 (Villoria 2019). Additionally, the allocation of land for food production, waste, and biofuels has been influenced by population growth, changing diets, and yield improvements, with animal product production dominating land use changes over the past 50 years (Hinrichsen 1998). These findings underscore the challenges posed by increasing food demand against a backdrop of shrinking agricultural land, highlighting the need for sustainable agricultural practices and potentially demand-side measures to regulate agricultural expansion in the future. On a per capita basis, the amount of land dedicated to agriculture worldwide has decreased from 1.45 hectares in 1961 to 0.61 hectares in 2020. Mongolia has the largest agricultural area per capita at 34 hectares, while Singapore has the smallest at 0 hectares. Notably, only 10 countries in the world have recorded a score of more than 10 hectares of agricultural land per capita, and merely 50 countries have an agricultural area greater than 1 hectare per capita (Figure 3).

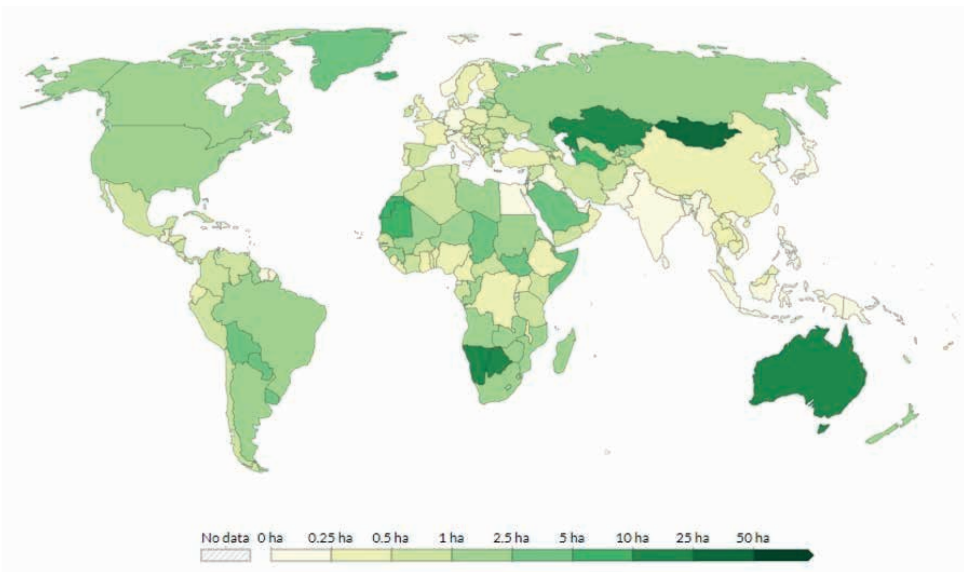

Figure 3. Arable land per capita in ha (FAO 2024).

When calculated as a percentage of the country's area, many states do not score more than 10%. This is true for most African and South American countries (the lowest percentage was recorded in Djibouti - 0.09%). In contrast, Southeast Asian and European countries have the highest scores (Bangladesh - 61%, Denmark - 59%, Ukraine - 57% and India - 52%). At the same time, however, it is worth pointing out that these are much more densely populated regions, with a much greater demand for agricultural products than in desolate regions (Figure 4).

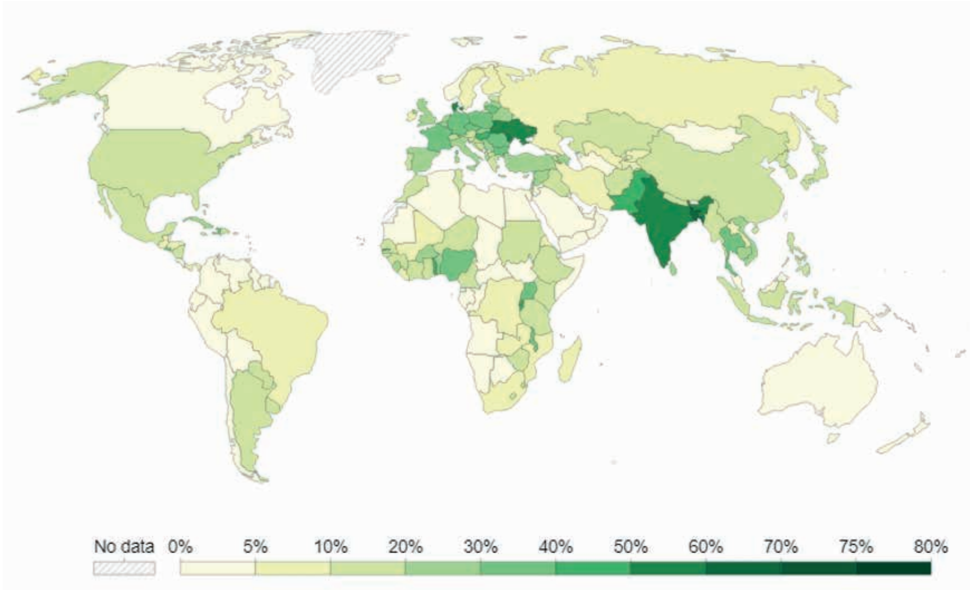

Figure 4. Percentage of cultivated soils by country in the world (FAO 2024).

Here is some information on the estimated percentage of cultivated soil areas on each continent, based on available data.

1. **Asia**:

Asia is the largest continent and has a significant percentage of cultivated land. It is estimated that 37.2% of the world's arable soils are in Asia. The countries with the highest proportion of arable soils are Bangladesh (62%) and India (52%). The country with the lowest value in the region is Oman (0.2%).

2. **Africa**:

Africa has a variety of soil and climatic conditions, which affects the proportion of cultivated areas. According to current data, 19.8% of the world's arable soils are in Africa. The countries with the highest proportion of arable soils are Togo (49%) and Burundi (47%). The area with the lowest value in the region is the Western Sahara Desert (0.1%).

3. **North America**:

North America also has a significant share of cultivated areas. Approximately 15.1% of the world's arable soils are currently located in North America. The country with the highest proportion of arable soils is the United States of America (17%). The country with the lowest value in the region is The Bahamas (0.8%).

4. **Europe**:

Europe, despite being a relatively small continent, has significant cultivated areas, particularly in countries such as Russia, France, Germany, Ukraine and the UK. An estimated 13.8% of the world's arable soils are located in Europe. The countries with the highest proportion of arable soils are Denmark (59%) and Ukraine (57%). The country with the lowest value in the region is Montenegro (0.7%).

5. **South America**:

South America has extensive agricultural areas, particularly in the Argentinian Pampas and Brazil. Approximately 10.5% of the world's arable soils are currently located in South America. The countries with the highest proportion of arable soils are Argentina (12%) and Paraguay (12%). The country with the lowest value in the region is Suriname (0.4%).

6. **Australia and Oceania**:

Australia and Oceania have limited cultivated areas due to their arid and desert nature. An estimated 3.5 per cent of the world's arable soils are located in Australia and Oceania. The countries with the highest proportion of arable soils are Tonga (28%) and Samoa (4%). The country with the lowest value in the region is Palau (0.4%). 4% of Australia's entire land area is covered by arable soils.

Please note that these figures are general and may vary according to different sources and specific assessment methodologies. Furthermore, the distribution of cultivated soils can also vary within a continent depending on local climatic, geological and economic conditions.

1.1.3 Degraded soils by continent

Estimating the exact percentage of degraded soils on each continent can be difficult due to differences in measurement methodologies and the lack of uniform data for all regions. Different studies employ diverse indicators and methodologies, leading to discrepancies in assessing soil degradation levels (AbdelRahman et al. 2023; Слабунова, Арискина 2022; Yusuf et al. 2019). For instance, research in the Nile delta and Rostov region utilized agrochemical soil indicators and indices to evaluate soil degradation, highlighting the complexity and variability in measurement approaches (Bell et al. 2021; Ayub et al. 2020). Additionally, studies in Nigeria and South Africa emphasized the importance of developing standardized methods for assessing soil degradation to ensure uniformity and accuracy in data interpretation. The global scale of soil degradation further complicates the issue, making it crucial to establish consistent measurement protocols and data collection practices to effectively monitor and address soil degradation challenges worldwide. Although gathering data on soil degradation across continents faces specific challenges due to differing measurement methodologies and a lack of uniform data for all regions, general information on this issue can still be provided. The report by Pandit et al. (2018) indicates that the most significant causes of degradation worldwide were deforestation, desertification, and the systematic reduction in the quality of arable soils (Figure 5). The majority of these phenomena can be attributed to increased human activity within the respective territories.

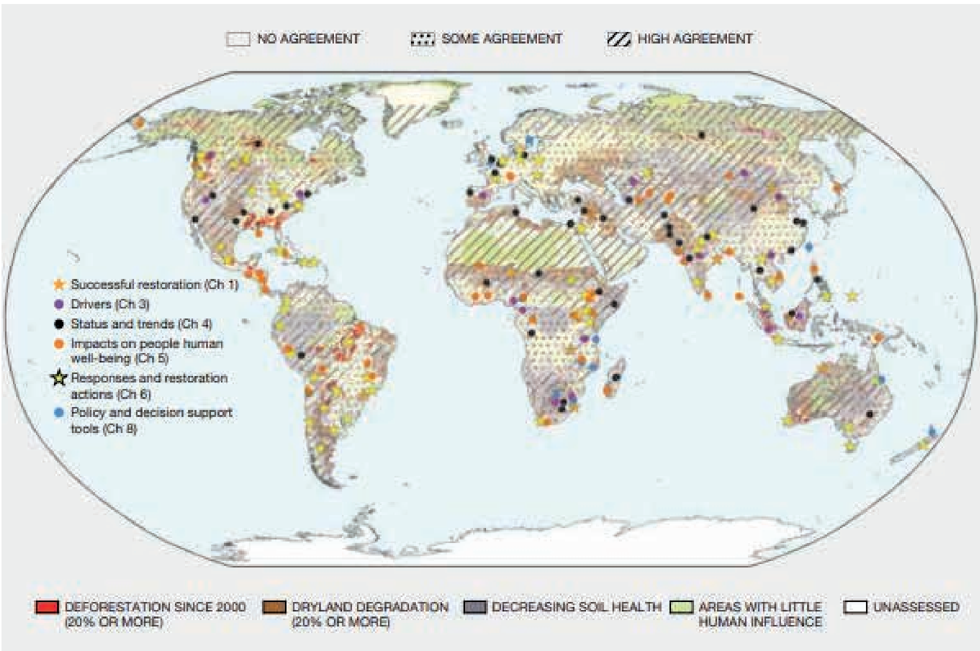

Figure 5. Areas of degraded soils in the world (Pandit et al. 2018).

According to the Living Planet Report (WWF 2016), the highest proportion of highly degraded soils was found in densely populated and urbanised areas, that is, Central and Eastern Europe, South-East Asia, the Mediterranean and Central Africa (Sprunger 2023). These areas face significant challenges due to factors such as land-use changes, climate change, and unsustainable agricultural practices (Cojocaru, Abramov 2023). In contrast, regions with low population density like north-eastern Russia, Canada, and Alaska exhibit greater soil stability (Tunçay, Başkan 2022). The degradation of soils in highly populated areas is exacerbated by anthropogenic activities, leading to a decline in soil quality, loss of biodiversity, and reduced land productivity (AbdelRahman et al. 2023). To address this issue, there is a growing need to implement sustainable land management practices to ensure soil health and mitigate the adverse effects of soil degradation on food security and ecosystem balance. In contrast, the soils with the greatest stability are those in areas with a low population density: north-eastern Russia, Canada and Alaska (Figure 6).

Figure 6. Degree of soil degradation worldwide (WWF 2016).

These conclusions are confirmed by an analysis of the area of non-degraded soils in the different countries of the world (Figure 7).

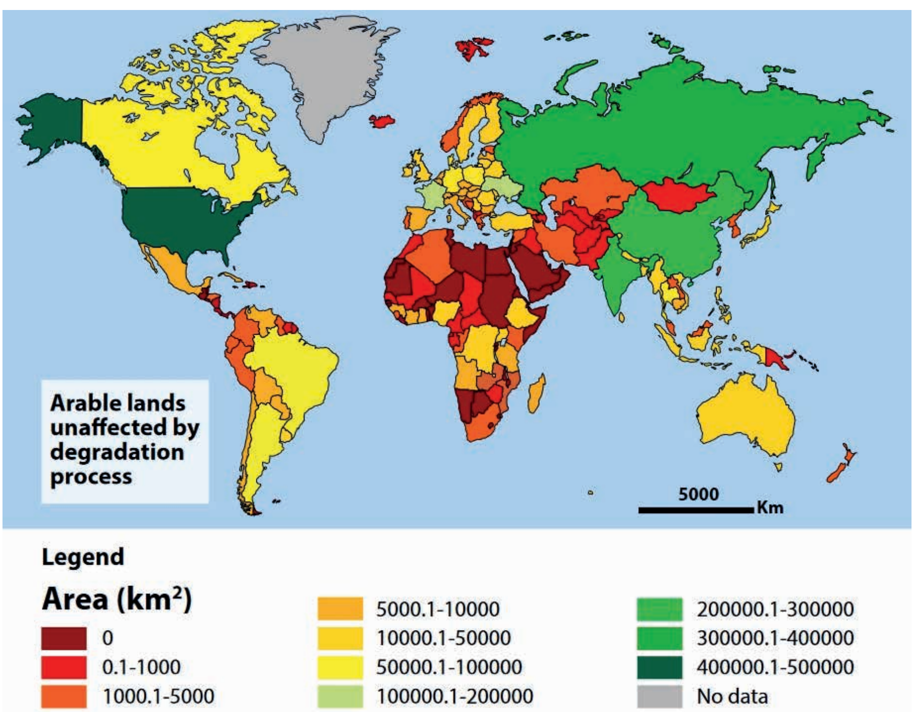

Figure 7. Area of soils not affected by the degradation process.

Source: own elaboration based on Prăvălie (2021).

1. **Africa**:

Soil degradation in Africa is a pressing issue, with around 50% of the continent's soils being degraded due to various factors such as erosion, deforestation, overgrazing, over-intensive agriculture, and drought (Sprunger 2023; Ekka et al. 2023; Raj et al. 2023). This degradation significantly impacts ecosystem integrity, biodiversity, and long-term ecological productivity, exacerbating climate change and habitat loss globally (Müller et al. 2023). Human-induced processes like land use transformation and overexploitation of natural resources contribute to this degradation, leading to a loss of carbon from vegetation and soil, further intensifying global warming (AbdelRahman 2023). The management of land degradation is crucial for environmental sustainability, with sustainable land use practices and better forestry management being key steps towards mitigating the adverse impacts of soil degradation on Africa's landscapes and ecosystems. Efforts to address soil degradation in Africa should focus on implementing nature-based solutions like sustainable land management and ecosystem-based perspectives to conserve and maintain the continent's land resources.

2. **Asia**:

Asia is also facing soil degradation, especially in regions with intensive agriculture, excessive use of chemical fertilisers and environmental pollution. According to current data, approximately 38% of Asia's soils are degraded. Soil degradation in Asia, particularly in regions with intensive agriculture, excessive chemical fertilizer use, and environmental pollution, is a significant concern. Studies show that approximately 38% of Asia's soils are degraded, impacting soil quality and fertility (Sprunger 2023; Liliwirianis et al. 2023; Kumar 2023; Jin et al. 2022). Factors contributing to this degradation include deforestation, overgrazing, conversion of forests to farmlands, and cultivation on marginal lands due to population growth and food demand (Lin et al. 2022). Research in China's rice fields revealed that as soil degradation progresses, concentrations of essential nutrients like nitrogen and phosphorus decline, affecting soil health and productivity. Additionally, degraded paddy fields in Southeastern China showed lower levels of total nitrogen, labile organic carbon, and phosphorus, emphasizing the urgent need for sustainable agricultural practices to mitigate further soil degradation and restore soil fertility.

3. **North America**:

In North America, soil degradation exhibits diverse dimensions influenced by various factors such as uncontrolled agricultural practices, water and wind erosion, and pollution, leading to around 21% of soils in the region being degraded (Sprunger 2023; AbdelRahman et al. 2023; Зайцев et al. 2022). The impact of soil degradation is significant, affecting the capacity of soils to support plant and animal life, regulate essential ecosystem services, and contribute to global climate change (Zhang et al. 2022). Different regions within North America face distinct challenges, with some areas experiencing salinity and alkalinity risks, compaction, and waterlogging, while others suffer from physical and chemical degradation due to unsustainable land management practices (Frühauf et al. 2020). The varying intensities and types of degradation processes highlight the need for region-specific strategies to mitigate soil degradation and promote sustainable land use practices across North America.

4. **South America**:

On the American continent, soil degradation manifests through erosion, deforestation, and over-intensification of agriculture, leading to an estimated 29% of South American soils being degraded (Sprunger 2023; Зайцев et al. 2022; Foucher et al. 2023; Gunawardena 2022; Macedo et al. 2023). The conversion of native vegetation to agricultural land, particularly for crops like soybeans, has significantly contributed to soil degradation in South America, impacting soil health and biodiversity. The misuse of agricultural techniques, changes in hydrological regimes, pollution from agrochemicals, and industrial emissions further exacerbate soil degradation, causing losses in soil fertility and humus content. Urgent conservation measures are necessary to mitigate the effects of land-use changes on soil erosion and sediment dynamics, preserving essential ecosystem services like nutrient cycling and water regulation in the region.

5. **Europe**:

In Europe, while soil degradation may not be as prevalent as in some other regions, certain areas face vulnerability to soil erosion and degradation primarily due to intensive agriculture and deforestation (Samarinas et al. 2023; Seeger 2023). Recent data suggests that approximately 12% of Europe's soils are degraded, highlighting the ongoing issue of land degradation within the continent (Ferreira et al. 2023). Factors such as unsustainable land use practices, including intensive tillage and overuse of agrochemicals, contribute to the degradation of agricultural land in countries like Portugal and Greece (Sprunger 2023). Additionally, the use of heavy machinery and the intensification of agriculture have led to a substantial increase in soil erosion rates in countries like Germany, further exacerbating the problem of soil degradation (AbdelRahman et al. 2023). These findings underscore the importance of implementing sustainable land management practices to mitigate soil degradation and preserve soil health across Europe.

Soil Atlas of Asia, Europe and Latin America

Land degradation is a widespread issue impacting all parts of the world and detrimentally affecting approximately 3.2 billion individuals, leading to a significant economic loss equivalent to 10% of the annual global gross product. This phenomenon is exacerbated by factors such as land use changes, deforestation, intensive agricultural practices, and climate change, which collectively contribute to soil degradation, loss of biodiversity, and reduced ecosystem services (Akça et al. 2022; Raj et al. 2023; von Keyserlingk et al. 2023; Tunçay, Başkan 2022; Sprunger 2023). The consequences of land degradation are far-reaching, threatening food security, socio-economic stability, and environmental sustainability on a global scale. Despite ongoing efforts by various organizations and institutions to address this issue, the complexity of land degradation dynamics and the lack of a consistent risk assessment framework hinder effective mitigation strategies, highlighting the urgent need for integrated approaches to combat this multifaceted challenge. In this context, restoring degraded land is an urgent priority in efforts to protect biodiversity and ecosystem services, which are essential for all life on Earth and to ensure human well-being. Pandit et al.'s (2018) report found that avoiding land degradation and rehabilitating degraded land makes economic sense, resulting in greater food and water security, increased employment and improved gender equality and helping to avoid conflict and migration. Avoiding land degradation and restoring degraded land are also essential to achieving the Sustainable Development Goals.

The main degradation processes include loss of soil at a faster rate than it is formed by erosion (by wind, water and root crop harvesting), nutrient removal, depletion of soil organic matter, sealing of the surface by urban development, pollution, compaction by heavy machinery and increasing salinity and acidity. These processes are primarily driven by excessive consumer demand for land resources, population growth, competition for soil-based ecosystem services, and a lack of effective planning and policies recognizing soil value (Зайцев, Собко 2022; Ekka et al. 2023; Saljnikov et al. 2022; Ferreira et al. 2023; Cojocaru, Abramov 2023). Inappropriate land management practices exacerbate these issues, with climate change further compounding the negative effects, emphasizing the urgent need for sustainable land management strategies and policies to mitigate soil degradation and ensure long-term soil fertility and productivity (Forster 1995).

Please note that the above estimates are general and may vary according to different sources and assessment methodologies. Soil degradation is a complex problem that can have many causes and effects, so the exact figures for each continent may vary depending on the specific areas and time of analysis.

According to various sources, land degradation affects approximately 2.6 billion people in a hundred countries, covering around 33% of the global land surface (Raj et al. 2023). Annually, a staggering 75 billion tons of soil are eroded from arable lands worldwide, with industrialized countries depleting soil at a rate 17 times faster than it takes to form a new arable layer (Akça et al. 2022). Energy production, food production, and transport contribute to about 80% of land degradation, exacerbating the issue on a global scale (Sprunger 2023). Soil degradation, stemming from factors like land conversion and intensive agricultural practices, could potentially lead to a 12% reduction in global food production over the next 25 years (Tunçay, Başkan 2022). These figures underscore the critical need for sustainable land management practices and policies to mitigate the adverse impacts of soil degradation on food security and ecosystem health (Rao et al. 2023).

Causes of soil degradation in Europe

Maintaining soil health is crucial for societal sustainability, yet soil faces escalating threats from various human activities, as highlighted in the provided research contexts (Panagiotakis, Dermatas 2022; Timmis, Ramos 2021; Strauss et al. 2023). The degradation of soil due to erosion, compaction, pollution, and loss of biodiversity poses a significant challenge globally, impacting essential services like food production and carbon sequestration (Luster et al. 2022). The new EU Soil Strategy emphasizes the importance of protecting and restoring soils for a sustainable future, aiming for healthy soil ecosystems by 2050 (Münzel et al. 2023). Efforts for sustainable soil management require consensus across stakeholders and the implementation of measures like organic fertilization, diversified crop rotation, and conservation tillage. Soil contamination, a major concern, necessitates proper utilization, management, and remediation to safeguard human health and ecosystem integrity. The threats to soil are complex, widespread, and continental in scale, underscoring the urgent need for coordinated global action to preserve this vital resource. For the sake of simplicity, these threats are presented separately. However, in reality, they are often related. When multiple threats are present at the same time, their combined effects tend to be a problem. Ultimately, if not counteracted, the soil will lose its ability to perform its functions (Berezin 1995). This process is known as soil degradation.

In the European Union, approximately 52 million hectares, which represents over 16% of its total land area, are impacted by various degradation processes. This issue is particularly pronounced in the newest Member States, where the extent of affected land rises significantly to 35%. The assessment of land degradation in the EU is crucial due to the challenges posed by human-induced global land change issues, such as those identified in the World Atlas of Desertification (WAD) and the Sustainable Development Goal (SDG) indicator 15.3.1, calculated using the Trends.Earth tool (Gianoli et al. 2023). Efforts to monitor and combat land degradation in the EU involve the development of Spatial Decision Support Systems (S-DSS) like the one offered by the LandSupport tool, which aims to provide valuable support to administrative units in evaluating and addressing land degradation issues at different spatial extents (Schillaci et al. 2023). Additionally, projects like NewLife4Drylands focus on using remote sensing and satellite data to monitor land degradation and restoration interventions, emphasizing the importance of accurate indicators and proxies for assessing land degradation status (Зайцев, Собко 2022).

Degraded soils in Europe exhibit varying characteristics based on regional differences and the specific causes of degradation, as highlighted in multiple research papers. Soil degradation processes differ significantly across Europe due to diverse factors such as climate, soil type, vegetation, and topography (Gantar et al. 2023). The rate of degradation of soil physical properties is influenced by the hierarchical structural organization of the soil mass and various degradation factors like compaction from heavy field equipment, prolonged use of mineral fertilizers, and irrigation practices (Sapozhnikov 1995; Kartini et al. 2023; Kavvadias et al. 2021). These factors contribute to soil compaction, erosion, contamination, and salinity, impacting agricultural areas in countries like Portugal and Greece (Ferreira et al. 2023). Additionally, the application of organic matter to degraded soils is emphasized to enhance soil stability and water-carrying capacity, especially in arid and semi-arid regions (Ma et al. 2022).

Here are some relevant details about the extent of soil degradation in Europe:

Soil erosion:

Soil erosion (Latin erosio - scaling) is one of the main causes of degradation in Europe. In a broad sense, it is the destruction of the surface layer of soil, consisting of the disintegration of its structure and the mechanical displacement of soil particles under the action of water force (water erosion) or wind (wind erosion) (Karczewska 2012). Areas highly susceptible to soil erosion are often characterized by intensive agriculture, steep slopes, drainless valleys, and coastal regions, where factors like wind and water contribute to the loss of fertile soil, diminishing its agricultural productivity. Studies in Mediterranean Europe (Nunes et al. 2022), and northern Italy (Pijl et al. 2020) have highlighted the impact of various land use practices, rainfall patterns, and topographical features on soil erosion vulnerability. These regions exhibit different degrees of erosion risk, emphasizing the importance of implementing sustainable land management practices to mitigate soil loss and preserve soil fertility for long-term agricultural sustainability. Factors such as wind and water lead to the loss of fertile soil, which in turn reduces its ability to support agriculture.

Climate, topography, and soil properties play crucial roles in determining the extent of erosion, with the Mediterranean region being especially susceptible to accelerated soil erosion due to its unique characteristics. The Mediterranean area experiences prolonged periods of drought followed by intense rainfall events, as highlighted in various studies (González-Pérez et al. 2023; Triano-Cornejo et al. 2023; Samela et al. 2022). These extreme weather patterns, combined with steep slopes and shallow soils low in organic matter, create a perfect storm for heightened erosion rates. Additionally, the randomness of the Mediterranean climate, with forecasts of reduced annual rainfall but concentrated in extreme events, further exacerbates the erosion potential in the region (Duarte 2022). Understanding and managing these physical factors are essential for developing effective strategies to mitigate soil erosion and preserve the fragile Mediterranean landscapes for sustainable agricultural practices and ecosystem health (Marien et al. 2024). The transition to agriculture and grazing in Neolithic times around the Mediterranean initiated a progressive deforestation process that has persisted over the centuries (Tomao et al. 2022; García-Ruiz et al. 2020). This deforestation trend is exemplified by the Ebro delta, where the development is closely tied to deforestation and the expansion of agricultural activities from the Middle Ages to the 19th century (Fuerst-Bjeliš et al. 2021). The impact of human activities on the landscape is evident in the rapid decline of arboreal pollen, conflicts over control of summer grasslands, and increased sedimentation rates due to intense erosion following deforestation (García et al. 2017). The introduction of agriculture and grazing during the Neolithic period led to the suppression of forest communities for land cultivation, ultimately resulting in the degradation of Mediterranean forests into maquis or bare rock in regions like the Adriatic-Mediterranean area (Brisset et al. 2020). In some parts of the Mediterranean, erosion has reached an irreversible stage, to the extent that in some places, erosion has virtually ceased because there is no longer any soil. This contrasts with north-western Europe, where soil loss is lower because rain falls mainly on gentle slopes and is more evenly distributed throughout the year than in the South. Consequently, the area affected by erosion is less extensive than in southern Europe.

However, erosion is still a major problem, especially off-road, in north-western and central Europe and is mainly increasing through surface erosion on bare soil surfaces.

Over-intensification of agriculture:

Intensive farming practices, characterized by the excessive use of chemical fertilizers, pesticides, and agricultural machinery, have been linked to soil depletion through various mechanisms. These practices contribute to soil erosion, loss of organic matter, increased soil acidity, and nutrient depletion, ultimately impacting soil health and productivity (Pereira et al. 2023; Reddy et al. 2023; Demir 2022). Studies have shown that uncontrolled intensive farming activities can disturb the physical, chemical, and biological properties of soils, leading to higher levels of certain elements like heavy metals in agricultural lands (Bedolla-Rivera et al. 2023). Additionally, the use of conventional soil management techniques in intensive agriculture has been found to have a negative impact on soil quality, with chemical indicators being the most prevalent in soil quality assessments (Ilampooranan et al. 2022). Furthermore, the legacy of intensive agriculture practices, such as excessive nitrogen application, has been implicated in soil and water degradation, highlighting the long-term consequences of unsustainable farming practices on soil resources.

Soil contamination:

Industrial pollutants, such as heavy metals, chemicals and toxic substances, may affect the quality and health of soils (Baran, Turski 1996). Some areas, especially those with heavy industry or historical pollution, may have degraded soils due to the accumulation of toxic substances.

Soil functions as a sink for various substances released into the environment by human activities, accumulating contaminants due to its unique filtering and buffering properties (Tarazona 2024; Hettiarachchi et al. 2023; Ansari et al. 2022; Rate 2022). Urban soils, in particular, are significant receiving environments for materials from different sources, acting as both sinks and sources of contaminants based on the persistence of added substances in the soil environment (Wang et al. 2022). Trace elements like Cd, As, Cr, Hg, Pb, Ni, Zn, and Cu, commonly found in soils, can originate from natural or anthropogenic sources, with some posing risks to ecosystems, food safety, and human health due to their varying levels of phytotoxicity and ecotoxicity. The complex interplay between soil and contaminants underscores the importance of understanding soil processes and implementing effective remediation strategies to mitigate the adverse effects of soil pollution on both the environment and human health. Many substances occur naturally in soils (e.g. heavy metals). When the concentration of these substances exceeds a certain level or is high enough to pose a potential risk to human health, plants, animals, ecosystems or other media (e.g. water), soils are considered “contaminated”.

Europe faces significant environmental challenges due to pollutants originating from various sources of human economic activity, leading to degradation across the continent. Air pollution, a major public health risk, is linked to adverse health effects such as cardiovascular diseases, lung cancer, and dementia (Gianoli et al. 2023). Fine particulate matter (PM) from anthropogenic activities significantly impacts urban areas in Europe, necessitating source attribution analysis to propose effective pollution reduction strategies (Boogaard et al. 2023). Additionally, socioeconomic factors like low education, wealth, and income influence residence locations in polluted areas, highlighting the impact of poverty on pollution exposure in European countries like Spain, Portugal, and France (Levasseur et al. 2021). Understanding the relationships between emissions from different sectors and the concentrations of pollutants like PM in European cities is crucial for addressing environmental degradation and improving public health (Bartík et al. 2023).

Soil contamination from local sources is often related to industrial plants that are no longer in operation, accidents or improper waste disposal. At industrial sites that are still in operation, soil contamination can be traced back to the past, but current operations still have a significant impact. Contaminated land is a consequence of a long period of industrialisation, consisting of uncontrolled production, the use of hazardous substances and unregulated waste disposal. Industrial development and the subsequent increase in industrial waste have led to significant environmental problems. Mining activities and former military sites also cause serious contamination (Bonetto et al. 2022; Zalesny et al. 2021).

Contaminated areas pose a significant threat to human health and the environment. Contamination of potable water, uptake of contaminants by plants, exposure to contaminated soil through direct contact, inhalation, and ingestion are the main risks (Alloway 1999).

Soil and groundwater contamination can be caused by production losses, industrial accidents and leaching of hazardous substances at landfills. The main contaminants include organic pollutants such as chlorinated hydrocarbons, mineral oils and heavy metals.

Areas with a high probability of soil contamination from local sources are concentrated in densely populated and industrialized regions, as supported by various research findings. Studies have shown that industrial activities, traffic emissions, and waste residue landfill significantly contribute to heavy metal pollution in industrial parks (Gao et al. 2023). Additionally, the presence of heavy metals like Cd, Hg, and Pb in industrial land poses severe health risks, emphasizing the importance of addressing soil contamination in these areas (Yuan, Wang 2023). Furthermore, research indicates that human-driven soil contamination is prevalent in urban greenspaces and natural ecosystems globally, highlighting the impact of human influence on soil contaminants and ecosystem sustainability (Kazyrenka, Kukharchyk 2022). Source apportionment studies have identified specific pollution sources such as agricultural activities, atmospheric deposition, and natural sources in different regions, emphasizing the spatial heterogeneity of pollution sources and the need for site-specific pollution prevention strategies (Liu et al. 2023). The largest and probably most affected areas are concentrated around industry, from the Nord-Pas de Calais in France to the Rhine-Ruhr region in Germany, through Belgium and the Netherlands and in large cities in the UK. Other areas where local soil contamination is likely, include the Saar region in Germany; northern Italy, north of the Po River area from Milan to Padua; the so-called Black Triangle located at the corner of Poland, the Czech Republic and Slovakia. However, contaminated areas exist around most major cities, and some contaminated sites also exist in sparsely populated areas.

Intensive agriculture, forestry, mining, transport, industrialisation and urbanisation in densely populated areas in Europe have led to interrelated problems of pollution and other forms of land degradation. In addition, some agricultural practices cause diffuse soil contamination through the direct application of pesticides, sewage sludge, compost, fertilisers and manure.

Continuous contamination can lead to the accumulation of hazardous substances in the topsoil (Forster 1995). The impact of soil contamination on soil functions, particularly buffering and filtering capacities, is well-documented in the literature. Soil pollution from various sources like industrial activities and improper waste management can alter the geotechnical properties of soils, affecting their ability to buffer and filter substances (Tarazona 2024; Naji et al. 2023). Contaminants such as heavy metals and toxins can disrupt these functions, leading to the release of harmful substances into the environment, potentially contaminating groundwater and surface waters (Zeliger 2022; Abubaker, Atasoy 2022). The degradation of soil functions like buffering and filtering capacity not only poses risks to the environment but also threatens human health and food safety, especially in agricultural settings where contaminated soils can impact crop yields and food security (Gasparatos 2022). Therefore, understanding and addressing the effects of soil contamination on these crucial soil functions are essential for environmental protection and sustainable land use management. Diffuse pollution from various sources poses significant challenges, with acidification, excessive mineral fertilizers, and heavy metal pollution being key concerns (Nsenga Kumwimba et al. 2023; Knightbridge et al. 2022). Acidification, primarily from sulphur and nitrogen compounds emitted by industry and transport, threatens soil health, forests, and water quality. Acidic soils can increase the mobility of metals like aluminium and cadmium, potentially harming plant roots and contaminating drinking water (Riddell et al. 2022). While sulphur emissions have decreased, the effects of historical emissions continue to impact ecosystems. Managing diffuse pollution requires addressing these issues comprehensively to safeguard environmental and human health, emphasizing the importance of understanding and mitigating the unintended consequences of various activities on water quality and ecosystems (Waeterschoot 2016).

Excessive nitrogen deposition is a significant driver of soil acidification in terrestrial ecosystems globally, with varying impacts observed across different regions (Chen et al. 2023; Wang et al. 2023). Nitrogen inputs can alter soil pH, affecting ecosystem structure and function, especially when inorganic nitrogen (IN) dominates over organic nitrogen (ON) inputs (Andreetta et al. 2022). Additionally, while nitrogen and phosphorus are crucial for plant growth, their excessive application through fertilization can lead to leaching into groundwater, potentially causing adverse effects on soil quality and ecosystem health (Seaton et al. 2023). Studies have shown that reductions in acid emissions are gradually aiding in the recovery of chronically acidified terrestrial ecosystems, although changing climate and land management practices can compromise this recovery process (Baer et al. 2023). Moreover, even in regions with carbonate-rich parent material, increased nitrogen deposition can contribute to soil acidification processes, highlighting the importance of managing nutrient inputs to prevent environmental degradation.

Based on critical load data, research indicates a decline in excess nutrient deposition by 2010 compared to 1990, with re-oligotrophication being a dominant trend in high-income countries while low-income countries still face widespread eutrophication (Devlin, Brodie 2023). However, in Central Europe, around 25% of areas exceed critical loads due to anthropogenic emissions, with NH_3 emission reductions showing limited potential to decrease exceedances (Ibáñez et al. 2023). Furthermore, human activities have significantly increased nitrogen deposition on terrestrial ecosystems, leading to various ecological effects and impacts on ecosystem services, affecting different beneficiary types through numerous pathways (Bieser et al. 2018). Despite efforts to reduce nutrient losses, half of the nitrogen exports to European coastal waters are from agricultural production, posing risks of coastal eutrophication that may worsen with global changes like socio-economic development and climate change (Clark et al. 2017; Ural-Janssen et al. 2023).

The deposition of heavy metals and potentially harmful elements leading to diffuse soil contamination is a significant issue globally, including in Europe. Research has highlighted the sensitivity of industrial regions to anthropogenic pollution, with extreme concentrations of heavy metals like Cd, Pb, Cu, Zn, Ni, Co, Cr, Fe, and Al found near aluminium plants in Hungary (Gasparatos 2022). Furthermore, the contamination of agricultural soils by heavy metals is recognized as a crucial factor in soil degradation (Rasulov et al. 2020). Industrial activities, such as industrial discharge and land application of fertilizers, contribute to the pollution of soil with harmful chemicals and heavy metals, impacting soil quality and plant growth (Vácha 2021). The accumulation of heavy metals in soil not only damages plant life but also poses risks to human health through the food chain, emphasizing the urgent need for remediation strategies to address this widespread issue (Ali et al. 2022; Manzoor et al. 2020). In forest soils, contamination is usually related to atmospheric deposition. In agricultural soils, heavy metals and other pollutants enter ecosystems as a result of fertilisers and animal manure, compost and pesticides. The application of contaminated sewage sludge poses a significant threat to soil ecosystems due to the presence of heavy metals, organic compounds, and pathogens (Lassoued, Essaid 2022; Zoomi et al. 2022). Long-term use of sewage sludge can lead to the accumulation of toxic heavy metals in soils, negatively impacting soil microbial populations and diversity (Dhanker et al. 2021; Urionabarrenetxea et al. 2022). Additionally, the presence of pollutants such as heavy metals, PAHs, and pesticides in sewage sludge can affect soil organisms like earthworms and plants, leading to adverse effects on soil health and biota . Furthermore, while radioactive fallout from Chernobyl in Eastern and Northern Europe still contributes to diffuse radioactive contamination of soils, the levels are lower than those observed in the late 1980s. This collective evidence underscores the potential risks associated with using contaminated sewage sludge and highlights the lasting impact of historical events like the Chernobyl disaster on soil quality.

Until now, great attention has been paid to diffuse contamination by cadmium, lead and mercury. Other potentially harmful substances include arsenic, chromium, copper, nickel, zinc and several persistent organic pollutants (POPs). A reduction in heavy metal deposition across Europe was to be expected following the implementation of unleaded petrol and the application of industrial emission reduction techniques (McBride 1994).

Deforestation:

Deforestation in Europe significantly contributes to soil degradation by removing natural forest vegetation, leading to the loss of soil-stabilizing roots and increasing the risk of erosion from wind and water activities (Sprunger 2023; Vieira et al. 2023). European Commission research highlights a dramatic increase in deforestation across Europe over the past two decades, with the area of deforestation being 49% larger in 2015-2018 compared to 2011-2015, and biomass loss increasing by 69% (Bezbradica et al. 2023). Moreover, 22 out of the 26 EU countries have escalated their harvesting rates, particularly impacting countries with large old-growth forests like Sweden, Finland, Romania, and Poland (Samec et al. 2022). This data underscores the pressing issue of deforestation in Europe and its detrimental effects on soil health and ecosystem stability.

Agriculture is the main driver of deforestation in all regions except Europe. The conversion of forests into farmland is a major cause of forest loss. According to the Food and Agriculture Organisation of the United Nations, it causes at least 50% of global deforestation, mainly for oil palm and soya production. Cattle grazing is responsible for almost 40% of global deforestation. In Europe, conversion to cropland accounts for about 15% of deforestation, and 20% is due to livestock grazing (Austin 2019).

Urban and infrastructure development significantly contribute to global deforestation, with construction and road expansion being the third largest cause, responsible for just over 6% of total deforestation (Kim 2022). In Europe specifically, urban and infrastructure development stands out as the primary driver of deforestation (Baehr et al. 2021). Additionally, overexploitation of timber, including for firewood, and illegal or unsustainable logging are identified as other detrimental human-related activities leading to deforestation (Andrade-Núñez, Aide 2020). The expansion of urban areas and infrastructure projects, such as airports and highways, has been shown to alter forest habitats, leading to forest cover loss and fragmentation, impacting biodiversity and ecosystem services (Güneralp, Xu 2021). These findings underscore the urgent need for sustainable land use planning and conservation efforts to mitigate the adverse effects of urban and infrastructure development on global deforestation.

Climate change is a significant driver of deforestation and forest degradation, creating a cyclical relationship with detrimental effects on both forests and the climate. Extreme events like fires, droughts, and floods, intensified by climate change (Ury et al. 2021), lead to forest loss and degradation, impacting biodiversity, soil erosion, and the water cycle. Additionally, deforestation amplifies carbon losses due to climate feedbacks, further exacerbating climate change (Li et al. 2022). Forest cover changes also influence local climate, affecting albedo, evapotranspiration, and surface temperatures (Sasidharan, Kavileveettil 2022). As forests play a crucial role in capturing CO_2, regulating the water cycle, and maintaining biodiversity, their loss due to climate change not only contributes to further climate impacts but also hampers the ecosystem services essential for a stable climate and healthy environment (Prevedello et al. 2019).

Land use changes:

Land use changes, including urbanization, intensive agriculture, and deforestation for agricultural or industrial activities, have been shown to contribute to soil degradation, leading to a decline in soil quality and health (Ordoñez et al. 2022; Sprunger 2023; Srejić et al. 2023). These changes result in the loss of soil fertility, erosion, and a decrease in biodiversity within the soil ecosystem (Padbhushan et al. 2022). Studies have highlighted that the conversion of forests to agricultural lands can significantly alter soil properties, impacting physicochemical variables and biological indicators, ultimately affecting soil resistance and stability . Additionally, research has demonstrated that land-use transitions from native forest lands to other uses, such as grasslands and cultivated lands, lead to substantial losses in soil organic carbon, microbial biomass, and other essential soil properties, exacerbating soil degradation and contributing to greenhouse gas emissions.

Salinisation:

Soil salinity, particularly prevalent in regions with low rainfall, can result in soil degradation by disrupting plant physiological processes and impeding crop growth, ultimately leading to soil structure deterioration. High salt concentrations in soils, as observed in arid and semi-arid areas, can elevate osmotic potential, affecting water movement within plants (Chanu 2023). This interference with water uptake can induce water stress in plants, impacting nutrient absorption and overall growth (Sharma et al. 2022). Additionally, soil salinity can lead to negative effects on crop nutrition and yields, further exacerbating soil degradation (Stan et al. 2022). Models like the Salt of the Earth (SOTE) model provide insights into how changes in salinity and sodicity influence soil hydraulic conductivity, crucial for understanding the risk of long-term soil degradation in regions with saline irrigation water (Kramer, Mau 2020; Kramer, Mau 2023).

Salinisation is the process by which soil accumulates excess mineral salts, especially water-soluble salts, in its structure. Excessive salt in the soil can lead to an ecological imbalance and create unfavourable conditions for plant growth.

Soil salinisation can occur as a result of various factors, such as:

- Too much salt in the irrigation water: When agricultural crops are irrigated with water containing high salt concentrations, the plants absorb the excess salts with the water, which then accumulate in the soil.
- Elevated groundwater levels: If the groundwater level is too high, it can lead to salts being washed from the deeper soil layers to the surface, where they are collected.
- Improper water management: Improper irrigation practices, such as over-watering plants, can lead to salt accumulation in the upper soil layer.
- Lack of adequate drainage: An inadequate soil drainage system can result in the flooding of soils and the retention of excess water, leading to salinisation.

Soil salinization poses a significant threat to agriculture and the environment, impacting plant growth and productivity (Ondrasek et al. 2022; Etesami, Noori 2019). Excessive salt in the soil leads to reduced water availability for plants, causing osmotic stress, nutrient deficiencies, and toxicity, ultimately resulting in decreased crop yields. Plants growing on saline soils exhibit various stress symptoms such as leaf drop, stunted root growth, and dieback, which further contribute to impaired growth and production. The negative effects of soil salinization are exacerbated by factors like poor soil structure, weak microbial activity, and low moisture retention, making it a pressing issue that requires effective management strategies to ensure sustainable agricultural productivity and environmental health.

In addition, mineral salts accumulating in the soil can have a detrimental effect on biological components, such as soil microorganisms, which can disrupt the functioning of soil ecosystems (Schnitzer, Khan 1978).

Preventing and managing soil salinization involves a multifaceted approach supported by scientific evidence:

1) Correct irrigation management, considering water quality and plant water requirements, is crucial (Ondrasek et al. 2022; Fu, Yang 2023).

2) Adequate soil drainage is essential to prevent waterlogging and excessive salt accumulation around plant roots (Bessaim et al. 2019).

3) Introducing salt-tolerant plants aids in reducing soil salinity levels by absorbing salts through their roots (Solomon, Arye 2023).

4) Additionally, organic practices like composting can enhance soil structure and water retention capacity, contributing to salinity mitigation (Ramamoorthy et al. 2021).

These strategies, ranging from irrigation adjustments to plant selection and organic soil management, form a comprehensive framework for combating soil salinization effectively and sustainably.

It is also important to monitor soil quality and act appropriately if salinisation occurs, in order to limit its negative effects and restore the balance of the soil environment.

Desertification:

Desertification, defined as soil degradation in arid regions, results from a combination of climatic factors like droughts and human activities such as deforestation and overgrazing, leading to the inability of the land to sustain vegetation (Zucca et al. 2022; do Nascimento 2023). The UNEP World Desertification Atlas highlights regions like central and south-eastern Spain, central and southern Italy, southern France, Portugal, and extensive areas of Greece as at risk of desertification (Entezari Zarch et al. 2021). This process not only has severe socio-economic impacts but also has the potential to destabilize societies and trigger population migrations (Adyanova et al. 2023). It is crucial to address both the climatic and anthropogenic drivers of desertification to mitigate its consequences and ensure the sustainability of affected regions.

Soil degradation across Europe is influenced by diverse factors like climate, soil type, and agricultural practices (Gianoli et al. 2023; Ferreira et al. 2023; Rust et al. 2022). Initiatives to combat soil degradation include sustainable agriculture practices, afforestation, erosion control measures, and the preservation of natural areas (Sprunger 2023; Kavvadias et al. 2021). In Mediterranean regions, severe erosion and low organic matter content contribute to soil degradation, highlighting the need for targeted interventions like the use of olive mill wastes for soil restoration. Understanding the causes and consequences of soil degradation is crucial for implementing effective conservation strategies and ensuring the long-term sustainability of agricultural lands across Europe. By integrating scientific knowledge with practical solutions, such as improved land management practices and stakeholder engagement, efforts to protect soils and mitigate degradation can be enhanced and tailored to specific regional challenges.

The Communication from the **European Commission to the Council and the European Parliament** identified eight main threats to soil: Soil sealing, erosion, loss of organic matter, decline in biodiversity, pollution, soil compaction, hydrogeological hazards, and salinization (Cioruța, Coman 2022). These threats are crucial to address as soil degradation processes like erosion, compaction, and pollution are widespread globally, emphasizing the urgent need for soil protection and sustainable management (Иванов et al. 2022; Panagiotakis, Dermatas 2022):

- **Soil sealing** occurs mainly through the development of technical, social and economic infrastructure, especially in urban areas. In 1996, 43% of the area on the Italian coast, generally containing fertile soil, was completely built up.
- **Erosion** is mainly caused by inappropriate soil use through agricultural and forestry practices, but also by development and uncontrolled water run-off from roads and other sealed surfaces. Over more than a third of the total Mediterranean area, average annual soil losses can exceed 15 tonnes/ha.
- **The loss of organic matter** is mainly explained by intensive agricultural land use, especially when organic residues are not sufficiently produced or recycled into the soil. Agronomists believe that soil containing less than 1.7 per cent organic matter is at the pre-desert stage.
- The **decline in biodiversity** is linked to the loss of organic matter, as biodiversity depends on organic matter, meaning that all soil biota live on organic matter.
- **Pollution** can be diffuse (widespread) or local and is caused by many human activities, such as industrial production and traffic, mainly through the use of fossil raw materials, such as ores, oil, coal and salts, among other things, or by agricultural activities.
- **Soil compaction** is a rather recent phenomenon, caused mainly by considerable pressure on the soil through high vehicle loads during agricultural and forestry land use. It is estimated that 4% of soils across Europe suffers from degradation caused by soil compaction.

- **Hydrogeological hazards** are complex phenomena, resulting in flooding and landslides, partly due to uncontrolled soil and land use (e.g. sealing, compaction and other adverse effects, as well as uncontrolled and other adverse impacts), and uncontrolled mining activities.
- **Salinisation** is mainly a regional problem, but in areas where it occurs, such as the Mediterranean basin and Hungary, agriculture, forestry and sustainable water resources are seriously threatened. It is estimated that 1 million hectares in the EU are affected.

The European Union's evolving Soil Protection Strategy, including the Soil Strategy 2030, emphasizes the importance of soil health, conservation, and its role in a circular economy, highlighting the need to protect soil as a fundamental resource for human health, wildlife, and climate (Zeiss et al. 2022). However, current policies and conservation actions have been insufficient in protecting soil biodiversity and ecosystem functions, with a lack of enforceable soil-related policies and conservation goals, indicating a gap in addressing these critical soil threats effectively (Heuser 2022).

In the first approach, it is important to analyse these risks in two ways:

- understanding the driving forces behind them and the resulting pressures that lead to adverse effects on the soil.
- understanding how the effects of these threats negatively impact the function of soils for humanity and the environment.

Issues to consider include the protection of open water and groundwater, the control of air contamination and pollution, the protection of the food chain through biomass production, the protection of human health when in direct contact with the soil and, finally, the maintenance of soil biodiversity, which is as important as biodiversity on the ground. An analysis of the consequences resulting from hazards is an absolute prerequisite for the development of operational or response procedures to mitigate these hazards.

Soil degradation in Europe is a multifaceted issue influenced by various factors beyond industrialization and transport. While industrial activities and transportation contribute to soil degradation (Bakacsi et al. 2023), other significant drivers include inappropriate farming practices, urbanization, habitat loss, and contamination from industrial activities (Frelih-Larsen, Bowyer 2022). Research highlights that soil degradation is a complex problem with multiple causes and no single solution (Rust et al. 2022). Agricultural land degradation, driven by unsustainable practices like intensive tillage and overuse of agrochemicals, is a global concern (Зайцев, Собко 2022). Moreover, the current state of agricultural landscapes shows a significant increase in eroded arable land due to factors like unfounded changes in hydrological regimes, pollution from agrochemicals, and industrial emissions (Ferreira et al. 2023). Therefore, addressing soil degradation in Europe requires a holistic approach that considers the diverse range of drivers impacting soil quality and sustainability.

Accurately identifying areas in Europe where soils have been degraded by industrialization and transport is a difficult task, as soil degradation is a complex process influenced by many different factors. Nonetheless, industrialization and transport can contribute to soil degradation in the following ways:

Industrial pollution:

Industrial activities are known to release a plethora of hazardous substances that can infiltrate the soil, impacting its health and fertility. Heavy metal pollution, toxic chemicals, and organic compounds discharged by industries pose a significant threat to soil quality, vegetation growth, and crop productivity (Velayatzadeh 2023; Rekha et al. 2022). These contaminants, including cadmium, mercury, arsenic, lead, chromium, and various organic compounds, can enter the soil through air pollution, industrial wastes, sewage sludge, and agricultural chemicals, ultimately affecting the food chain and human health. Studies have shown that industrial effluents can lead to genotoxic and mutagenic effects on agricultural soil, emphasizing the urgent need for remediation strategies to mitigate the adverse impacts of industrial pollution on soil ecosystems and crop quality.

Industrial land use:

The construction and development of industrial areas can lead to a change of use of agricultural or natural land to industrial land (Wang i in. 2020). Land use change can lead to loss of soil fertility, reduced organic matter and reduced soil biodiversity. Studies from various papers support this notion. For instance, research in Karnataka, India, found that rezoning agricultural land for industrial use led to increased firm creation and employment, impacting surrounding areas as well (Blakeslee et al. 2022). Additionally, a study in China highlighted how land-use changes in resource-based cities affect green land use efficiency, emphasizing the importance of rational industrial structure for sustainable development (Chang et al. 2023). Furthermore, investigations in Ethiopia demonstrated that land-use changes, such as deforestation for industrial purposes, can deplete soil organic carbon and nitrogen stocks, altering soil quality and organic matter fractions (Ahmed et al. 2022). These findings collectively underscore the critical link between industrial development, land use change, and soil fertility decline.

Transport-related emissions:

Transport, particularly road transport, can contribute to soil degradation through exhaust emissions and atmospheric pollutants. Transport-related emissions can settle on the soil surface, leading to contamination and reduced soil quality. Studies have shown that road transport is a major source of environmental pollution, with emissions from vehicles contributing to the release of microplastics from tires, which contaminate soil samples and road dust (Worek et al. 2022). Additionally, the impact of road transport on the environment extends beyond atmospheric emissions, as each stage of a vehicle's life cycle generates waste harmful to the environment, necessitating a comprehensive assessment of emissions into the atmosphere, soil, and wastewater to mitigate negative effects (Markina et al. 2022). Furthermore, research on heavy metal accumulation in soils and plants near motorways highlights the correlation between soil and plant contamination by pollutants emitted from vehicular traffic, emphasizing the role of transport in soil pollution and degradation (Кропова et al. 2022).

Unfortunately, there is a lack of clear data on the percentage of soil degradation in Europe resulting directly from industrialisation and transport. The process of soil degradation is usually the result of a combination of factors, and individual factors can interact with each other. It is important to take action at both an industrial and transport level to reduce negative impacts on soils through sustainable practices and environmental regulations.

Regions degraded in Europe by industry and motorisation

Here are some examples of the European regions most affected by soil degradation due to industry and motorisation (see Figure 8).

Figure 8. Main areas of industrialisation in Europe (Sokolenko et al. 2021).

Industrial areas in Germany:

As one of Europe's major industrial centres, many areas of Germany are particularly affected by soil degradation due to industrial activities. The Ruhr region, a former coal mining and heavy industry area, is experiencing problems with soil contamination and chemical pollution.

Northern Italy:

Northern Italy, especially Lombardy and the Italian Po Valley, is known for its developed industry and heavy traffic. Soil contamination is a problem in these areas, especially related to car emissions and industrial air and waste emissions.

Industrial areas in Poland:

There are many industrial areas in Poland, such as the Upper Silesian Industrial District, which has a long history of mining and heavy industry. These areas often suffer from soil degradation problems, such as chemical contamination, nutrient depletion and loss of soil capacity to support vegetation.

Metropolitan areas:

Large metropolitan areas in Europe, such as London, Paris and Berlin, are vulnerable to soil degradation due to increased traffic, air emissions and urbanisation. These areas are often characterised by nutrient depletion, poor soil quality and limited capacity to support agriculture and green spaces. However, it should be noted that soil degradation is not limited to these listed areas (Figure 9).

Figure 9. Major industrial regions in Europe (Pearson Education 2016).

In various regions, including Europe, industrial activities and motorization can significantly impact soil quality, leading to pollution and environmental degradation (Wang et al. 2022; Tarazona 2024). To mitigate these negative effects, it is crucial to implement protective measures such as pollution monitoring, sustainable industrial practices, and the preservation of green spaces and agricultural land (Perrone et al. 2022; Li et al. 2022). Research emphasizes the importance of managing soil environmental quality through risk control standards, as seen in China's classification system for soil quality assessment (Rasulov et al. 2020). Additionally, comparative analyses of soil environmental standards across different countries highlight the need for standardized derivation methods and improved indicators for effective pollution control and prevention. By adopting these strategies and incorporating lessons from global research efforts, Europe can work towards safeguarding its soils and promoting sustainable land use practices.

1.1.5 Areas in need of soil remediation in Europe

There are many areas in Europe that need to heal their soils through remediation. Here are some examples of such areas:

Mining and industrial areas:

Intensive extraction of natural resources like coal, metal ores, and oil deposits leads to severe soil degradation, as evidenced by various studies (Kucher et al. 2023; Zhang et al. 2022; Gantar et al. 2023; Miu et al. 2022). Soil remediation in these areas involves multiple strategies, including the removal of industrial waste, restoration of degraded land, rebuilding soil structure, and rehabilitation of the organic layer. Research highlights the importance of using organic amendments like biochar, compost, and activated carbon to improve soil quality and support plant growth without affecting metal bioavailability (Lebrun et al. 2022). Additionally, the application of engineered soils with suitable properties is crucial for recultivating degraded sites, ensuring they can provide ecosystem services and support agricultural activities. These findings emphasize the significance of comprehensive soil restoration approaches in regions impacted by intensive natural resource extraction.

Intensively used agricultural areas:

Intensive agriculture practices, characterized by the heavy use of chemical fertilizers and pesticides, have been linked to soil degradation and reduced vegetation support (Pereira et al. 2023; Martins et al. 2023). This degradation can lead to soil depletion, impacting the soil's ability to sustain plant growth and ecosystem services (Demir 2022). Scientific evidence suggests that implementing sustainable farming practices like crop rotation, composting, the use of natural fertilizers, and erosion-minimizing techniques can aid in soil remediation in these areas (Mishra et al. 2023). Conservation tillage systems, such as no-tillage, have been shown to mitigate the negative effects of microbial diversity depletion and enhance soil health and functionality, crucial for sustaining critical ecosystem functions like soil detoxification in tropical agroecosystems (Prescott et al. 2021). Therefore, adopting these sustainable practices is essential to restore soil health and promote long-term agricultural sustainability in areas affected by intensive agriculture.

Areas heavily affected by industrial and urban pollution:

Regions affected by heavy industrial and urban pollution, such as industrial areas, waste disposal sites or former industrial sites, may have degraded soils due to the accumulation of toxic substances. The remediation of soils in these areas may require the removal of contamination, phytoremediation techniques (the use of plants to clean the soil) or chemical techniques such as the extraction of toxic compounds (Greinert, Greinert 1999).

Areas degraded by erosion:

Areas prone to soil erosion, like steep slopes and degraded lands, require reclamation strategies to enhance soil fertility and stability. Research emphasizes the importance of revegetation and soil conditioning techniques in such areas (López-Vicente et al. 2023; Gastauer et al. 2022; wang et al. 2022; Tang et al. 2022). Implementing erosion control measures such as terracing, planting soil-retaining plants, and restoring natural vegetation are crucial steps in mitigating soil erosion and promoting sustainable land management (Mosier et al. 2021). Studies highlight the significance of revegetation projects in enhancing vegetation cover and stabilizing steep slopes, especially by utilizing plant functional traits adapted to challenging environments. Additionally, the use of perennial cropping systems in degraded lands can restore soil fertility effectively while providing multiple ecosystem services, contributing to long-term soil health and productivity. By combining these approaches, it is possible to reclaim and rehabilitate eroded areas, ensuring soil stability and fertility for sustainable land use practices.

It is important to identify specific areas that need soil remediation based on local conditions, land use history and causes of degradation. Appropriate soil remediation strategies and techniques must be tailored to the specific needs of each area to restore soil health and functionality (Gonet 2007).

There are several regions in Europe that require urgent soil remediation due to severe degradation. Here are some of these areas:

Donetsk Basin (Ukraine): The Donetsk Basin in Ukraine faces severe soil degradation due to coal mining and heavy industry activities, leading to chemical contamination, loss of soil structure, and declining groundwater levels, necessitating immediate remediation efforts. Research indicates that spoil tips covering a significant portion of the territory alter the land's topography, decrease soil fertility, and contain high levels of heavy metals (Kucher et al. 2023). Bioremediation using microorganisms from mine tips shows promise in reducing soil pollution with heavy metals and oil compounds (Faskhutdinova et al. 2021). The closure of mines in the region, especially through "wet conservation", highlights the need for post-mining measures to prevent dangerous geological changes and protect the environment (Trofymchuk et al. 2021). Additionally, the environmental risks associated with coal mining enterprises in the Donetsk region emphasize the critical need for minimizing threats and risks to prevent ecological disasters (Ulytsky et al. 2021). Studies on the distribution of toxic elements in the rock mass mined from the mines in the Donetsk-Makiivka area further underscore the environmental challenges posed by coal mining activities in the region (Ishkov, Kozii 2020).

North-western part of the Chernobyl exclusion zone (Ukraine): Research on the Chernobyl Exclusion Zone (CEZ) provides valuable insights into the radioactive contamination affecting the north-western part of the zone in Ukraine after the 1986 nuclear accident. Studies show that radionuclides like 137Cs, 90Sr, and Pu isotopes remain mobile in the environment, impacting soil and groundwater (Bugai et al. 2022). Additionally, investigations into vegetation dynamics within the CEZ reveal long-term radiation effects, with vegetation adapting to increased radioactivity levels (Gemitzi 2020). The vertical migration of radionuclides in soils near the Chernobyl Nuclear Power Plant Unit 4 underscores the urgent need for soil remediation to mitigate radioactive contamination and restore the soil's ability to support vegetation (Santos et al. 2019). These findings emphasize the necessity of remediation efforts to address the persistent radioactive contamination in the area and facilitate the recovery of the ecosystem for sustainable vegetation growth.

Romania: In some areas of Romania, such as the area associated with the mining and metallurgical industry near the town of Baia Mare, the soils have been seriously contaminated. Soil remediation in these areas is important to protect the environment and public health.

Regions of intensive agriculture in Western Europe: In some regions of Western Europe with intensive agriculture, soils have been impoverished and degraded due to the excessive use of chemical fertilisers and pesticides. Urgent soil remediation in these areas is necessary to restore ecological balance and sustainable agricultural and food production

Mediterranean coasts: In some areas of the Mediterranean coast, such as the agricultural areas in southern Spain, soil degradation has been caused by an excessive use of water resources, soil erosion and salinisation. Urgent restoration measures are needed to protect soils from erosion, restore fertility and ensure sustainable water resource management.

Approximately 19% of the registered industrial sites in Europe require or may require remediation or risk reduction measures, including remediation (Pérez, Eugenio 2018).

Significant progress has been achieved in identifying sites with historical activities contributing to environmental pollution, particularly in the European Union. By 2016, a total of 694,000 nationally registered sites had been pinpointed, with over 240,000 of these sites necessitating or undergoing detailed investigations to assess risks to both human health and the environment. Among the countries involved in the research, Finland, Norway, Denmark, Belgium, and Austria collectively accounted for more than 10,000 of these identified sites (Wilhelm et al. 2023). This data underscores the magnitude of the issue of historic pollution across Europe and highlights the urgent need for comprehensive strategies and interventions to address the environmental and health risks posed by these contaminated sites (DuBay et al. 2023) [Figure 10].

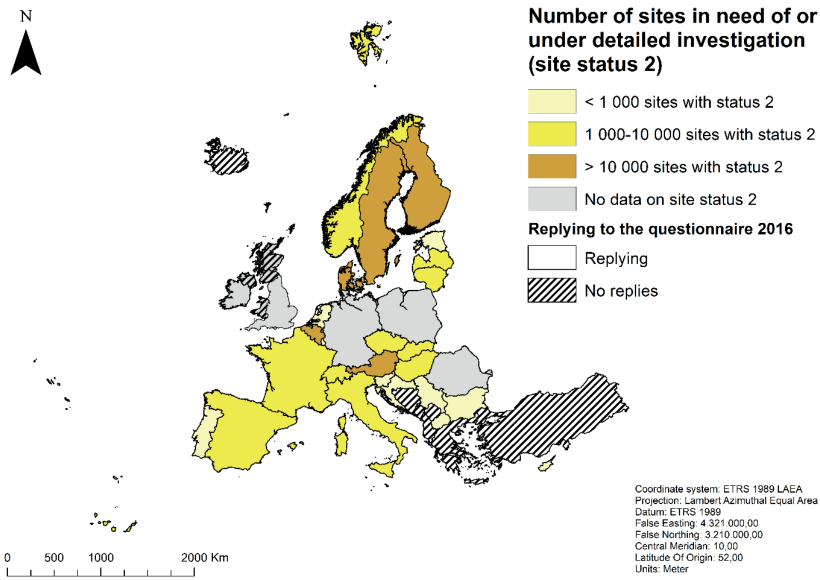

Figure 10. Number of degraded areas in EU countries.

Source: own elaboration based on Pérez and Eugenio (2018).

As things stand, around 65,500 sites have already been remediated or are currently under remediation (Falconi 2018). Among European Union countries, Belgium (Flanders) and Luxembourg recorded the highest density of sites undergoing successful restoration. This was followed by Denmark and Switzerland, respectively (Figure 11).

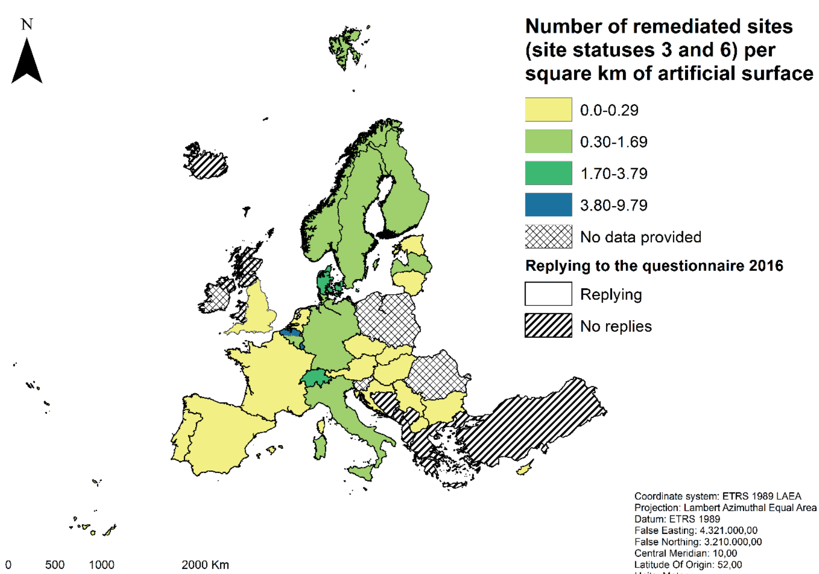

Figure 11. Area of reclaimed land in EU countries.

Source: own elaboration based on Pérez and Eugenio (2018).

In addition, Germany and Finland adopted national legislation on soil contamination at the end of the 20th century and have made significant progress in CS research and remediation, as evidenced by the high number of remediated sites. Poland, Ireland, Romania and the Balkan Peninsula countries were not included in the study. Detailed data for Poland is provided in subsection 1.1.6.

It is worth noting, however, that soil remediation needs may exist in different parts of Europe, and local conditions and problems may vary from region to region. Soil remediation is an important activity to restore soil health and functionality, and the scale and priorities of remediation activities should be determined on the basis of a thorough assessment of local conditions and needs.

1.1.6 Soil structure in Poland

Poland's soils exhibit significant structural diversity, as evidenced by various research papers. Alluvial soils, known as mady, cover less than 5% of Poland but are crucial for agriculture, forestry, and ecosystem functioning due to their specific location in river valleys and high productivity potential (Kabała 2022). In the loess-belt of SW Poland, diverse chernozemic soils with different features like mollic horizons, base cations, and bedrock variations are prevalent, leading to variable soil classifications (Łabaz et al. 2019). Fungal genetic diversity studies in Pulawy, Poland, highlighted the impact of soil type and pH on fungal communities, showcasing the diverse microbial populations in different soil types (Grządziel, Gałązka 2019). Additionally, carbonate-rich soils in the Pieniny National Park area demonstrate a range of properties influenced by carbonate content, mineral composition, and parent material, further emphasizing the structural diversity of Polish soils (Kiryluk-Dryjska, Więckowska 2020). Understanding this soil structural diversity is therefore critical for effective soil management to maximize agricultural yields, conserve biodiversity and protect the environment.

There are several dominant soil types in Poland, the most important of which are brown soils, podzols and chernozem (Figure 12).

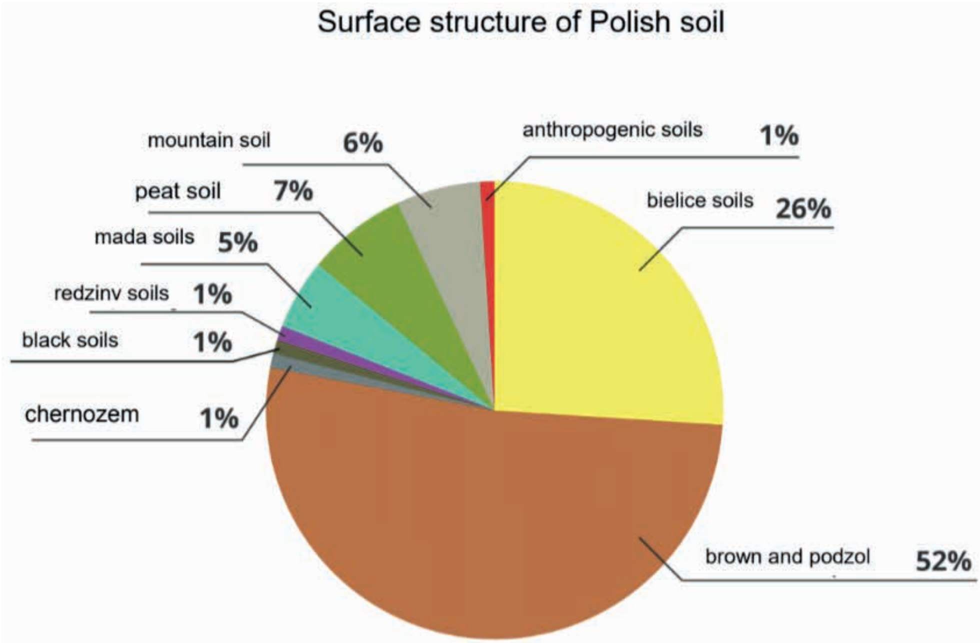

Figure 12. Surface structure of Polish soils; source: own elaboration based on zpe.gov.pl (accessed on 10 June 2024).

Podzolic soils in Poland, particularly in the north and north-east regions, are prevalent, known for their light color and low humus content (Blashik et al. 2022). These soils are typically sandy or sandy loam, impacting their water retention capacity and nutrient availability (Musielok 2022). Research has shown that podzolic sandy loamy soils in Poland can have a low supply of sulfur available to plants due to their light granulometric composition and low humus content, necessitating the inclusion of sulfur-containing fertilizers in cultivation systems to enhance nutrient availability and crop yield (Jankowski 2014). Additionally, studies have highlighted the importance of fertilization in correcting the low content of chemically active organic substances in podzolic soils, indicating that long-term use of organic and mineral fertilizers can stimulate the formation of humic acids and improve soil quality (Skrylnyk et al. 2022).

In Poland, brown soils are prevalent, particularly in the temperate zone, as indicated by the study on soil organic matter management (Kopiński, Witorożec 2022). These soils are characterized by their dark brown color and moderate humus content, making them fertile and well-drained, which is beneficial for agricultural crop cultivation. However, the properties and structure of brown soils can vary across different regions of Poland, reflecting the diverse agricultural landscape of the country. The presence of brown soils in Poland aligns with the broader context of soil types and their distribution within the country, highlighting the importance of understanding regional soil variations for effective agricultural practices and land use planning.

Chernozem soils in Poland, particularly in the southern plains, are characterized by high humus content, making them highly fertile (Weber et al. 2023; Dmitrievtseva et al. 2022). These soils exhibit a black color and exceptional structure, providing excellent water retention and nutrient availability for plant growth (Dudek et al. 2022). Research on humin fractions isolated from Chernozems in Poland has shown that these soils have a high content of humic substances, contributing to their fertility and carbon sequestration capabilities (Польовий et al. 2022; Weber et al. 2022). Additionally, studies on the dynamics of humus content in different regions of Poland have highlighted the importance of maintaining and improving the humus state of soils through proper agricultural practices to enhance soil fertility and productivity. Therefore, the scientific evidence supports the assertion that chernozem soils in Poland are characterized by high humus content, black color, and excellent fertility due to their unique structural properties and organic composition.

There are also other soil types, such as flat soils, mud soils, peat soils and swamp soils. Each of these soil types has its own specific characteristics that affect their agricultural use, water retention capacity and suitability as a habitat for different organisms.

Understanding the characteristics of soils (in Poland) is crucial for adapting cultivation techniques, fertilization, and other farming practices to specific soil conditions. Soil properties influence various processes like nitrification, denitrification, mineralization, and organic matter precipitation and dissolution (Sharma et al. 2023). Farmers' knowledge of soil properties and management practices is essential for addressing soil-borne pests and diseases, which significantly impact crop production in smallholder farming systems (Kumar et al. 2023). Additionally, historical knowledge from ancient civilizations emphasizes the importance of soil fertility in the development of agriculture and civilizations, showcasing the long-standing connection between soil characteristics and successful farming practices (Stepan, Ivaniuk 2022). Furthermore, the study on agroforestry in Madagascar highlights how farmers adapt their practices based on changes in soil fertility, demonstrating the importance of understanding soil-agrobiodiversity interactions for sustainable farming practices (Ngoya et al. 2023). The analysis of soil structure in Poland is also important in the context of monitoring soil changes, identifying areas with high agricultural potential and protecting soils as a valuable resource for our planet.

Analysing data from the Central Statistical Office (GUS 2021), it should be noted that the structure of Poland's land use is changing considerably, as shown in Table 1.

The share of agricultural land decreased from 65.9% in 1938 to 51.6% in 2009 (Table 1), while the area covered by forests and woodland increased from 20.8% in 1946 to 29.7% in 2009. However, it should be borne in mind that the actual area covered by forest and woodland is much larger, proportionally speaking, than the percentage we have here according to the Polish Central Statistical Office (GUS 2021), which estimates this figure to be around 33%. This is explained by the fact that part of the arable land acreage has been covered with self-sown woodland and mid-field scrub. This was influenced by the large areas of wasteland created as a result of the transformation of the political system after 1989. Since then, there has been a drastic change in the forms of land use in Poland. The area of set-aside and fallow land increased from 16,300 ha in 1990 to 1,289,000 ha in 2000. However, this figure gradually decreased in subsequent years, dropping to 179,000 hectares in 2020, for instance.

Table 1. Changes in the structure of land use.

Years	Grand total	Agricultural land		Forests and woody land	Other
		total	of which arable land		
	percentage				
1938	100.0	65.9	52.7	21.8	11.4
1946	100.0	65.6	51.3	20.8	13.7
1950	100.0	65.6	51.3	21.9	12.5
1960	100.0	65.5	51.2	24.5	10.0
1970	100.0	62.5	48.3	27.3	10.2
1980	100.0	60.3	46.7	27.7	12.0
1990	100.0	59.3	45.7	28.0	12.7
1995	100.0	57.4	44.4	28.2	14.4
2000	100.0	57.0	43.8	28.8	14.2
2005	100.0	50.9	39.1	29.3	19.8
2010	100.0	49.6	35.0	29.8	20.6
2011	100.0	49.4	35.3	29.9	20.7

Source: own elaboration based on GUS (2021).

Degraded land, characterized by a distorted structure and relief, poses a significant challenge in the land-use structure of countries like Ukraine, Poland, and Latvia (Novakovska et al. 2018; Sikorska-Maykowska, Strzelecki 2005). The decline in soil fertility due to various factors such as intensive agriculture, pollution, and deforestation has led to the degradation of vast tracts of land globally (Gupta 2019). In Poland, the Law on the Protection of Agricultural and Forestry Land defines degraded land as areas with reduced agricultural or forestry value resulting from natural deterioration, environmental changes, and industrial or agricultural mismanagement (Stepina 2022). This definition aligns with the global understanding of degraded land as territories where previous economic activities have left lasting negative impacts, necessitating restoration efforts for sustainable land use and environmental health. Efforts to address degraded land involve comprehensive mapping, assessment, and remediation strategies to mitigate the adverse effects of land degradation on ecosystems and human well-being. Devastated land, on the other hand, is defined as land that has completely lost its use value as a result of the deterioration of natural conditions or environmental changes and industrial activities, as well as faulty agricultural activities.

Both degraded and devastated land require rehabilitation and development. As can be seen from Table 2, devastated land with a deformed structure and relief and degraded land in need of rehabilitation and development in 2020 accounted for a total of 62,482 ha (Figure 13). At the time, only 1040 ha had been rehabilitated and 511 ha had been developed.

Table 2. Degraded and devastated land area in Poland.

Damaged and degraded land requiring reclamation and development, as well as reclaimed and developed land [ha]									
Land		1990	1995	2000	2005	2010	2015	2017	2020
Devastated and degraded		93679	72245	71473	64978	61161	62973	62038	62482
Rehabilitated (within the year)		2665	2698	2235	1861	1222	1807	1313	1476
Including the purpose of:	agriculture	1607	1028	456	555	634	1262	782	1040
	forestry	521	1434	1345	608	440	282	227	217
Developed (within a year)		2264	1864	1222	1132	581	852	519	511
Including the purpose of:	agriculture	1545	628	254	374	299	627	314	388
	forestry	370	1213	830	266	212	98	83	73

Source: own elaboration based on GUS (2021).

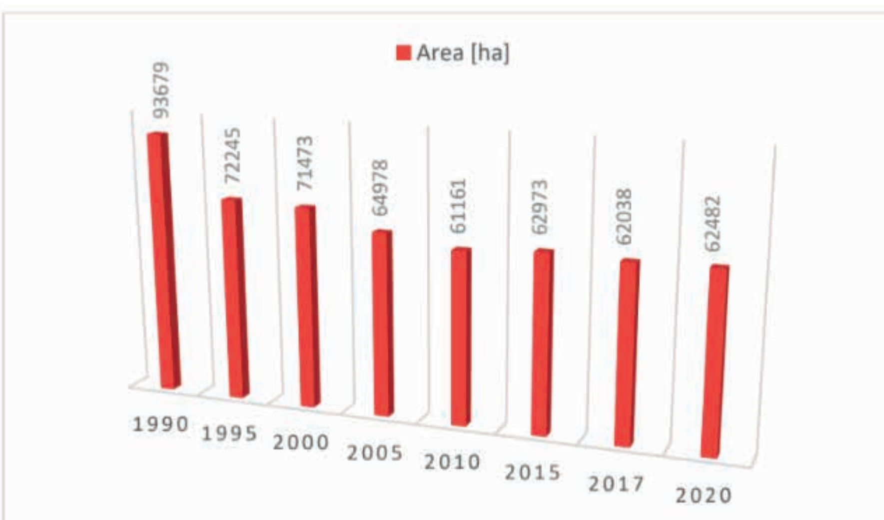

Figure 13. The extent of damaged and deteriorated land in Poland that needed rehabilitation between 1990 and 2020. Source: own elaboration based on GUS (2021).

The main causes of soil degradation in Poland include mining and quarrying, responsible for 63.2% of degradation (Figure 14). Meanwhile, energy, gas and water supply and metal production are among the minor causes of this phenomenon (Gonda-Soroczyńska, Kubicka 2016).

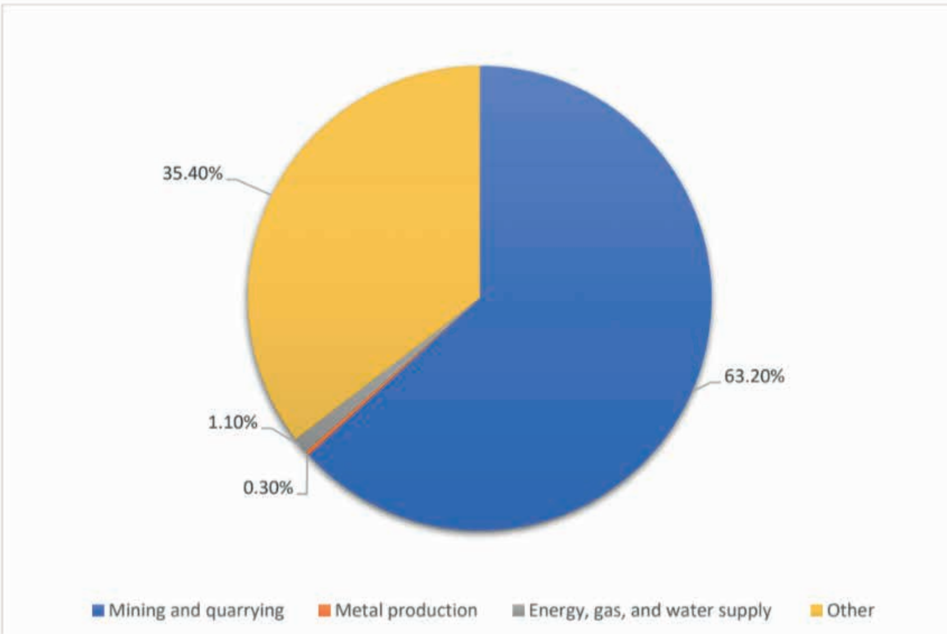

Figure 14. Areas necessitating remediation due to anthropogenic land use activities. Source: own elaboration based on Gonda-Soroczyńska and Kubicka (2016).

The map below summarises the share of devastated and degraded land in each province, as well as the area of land that has been rehabilitated and developed. Among the most degraded are the provinces of Silesia, Lower Silesia and Greater Poland, which are associated with mining and industrial activities. The Lubuskie and Podkarpackie voivodeships (provinces) are among the least degraded (Figure 15).

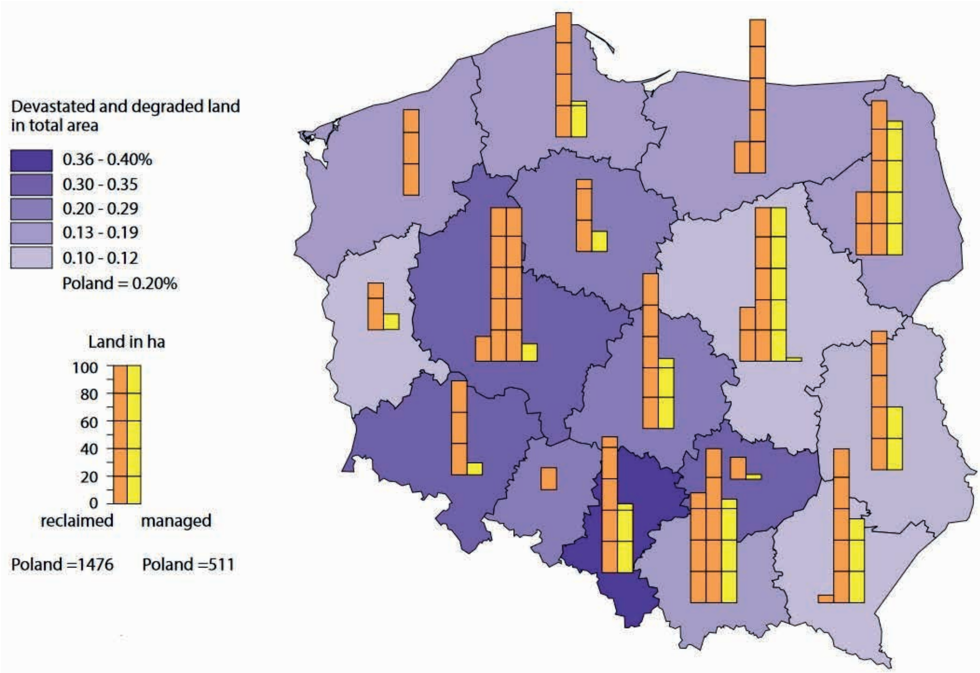

Figure 15. Areas of land requiring reclamation in Poland (GUS 2021).

1.3. SOIL FUNCTIONS IN THE ECOSYSTEM

Soil plays an extremely important role in the ecosystem, performing a variety of functions that are vital to life on Earth (Blum 2005). It is not only a substrate for plants, but also provides an environment for many organisms, influences the water cycle and the composition of the atmosphere, and acts as a buffer for various chemicals.

One of the main functions of soil is to **provide plants with essential nutrients**. The soil is a storehouse of minerals, such as nitrogen, phosphorus, potassium, as well as micronutrients essential for plant growth and development. Through the processes of mineralisation, decomposition of organic matter and interactions with micro-organisms, the soil releases these components in a form that is available to plants. This allows plants to take up essential substances from the soil and maintain their healthy condition (Banwart et al. 2017).

Soil also has an important **water retention function**. The structure of soils and the presence of organic matter affect the ability of soils to retain rainwater, which is crucial for regulating its circulation in nature. Soils act as a natural reservoir, storing water and allowing it to be gradually released to plant roots and underground water sources. In addition, soils act as a filter, cleansing water of various contaminants before it enters rivers, lakes or wells (Keesstra et al. 2012).

Another important soil function is its role **in the organic matter cycle**. Decomposition processes of organic matter in soils contribute to the transformation of organic matter into more stable forms such as humus. Humus is the organic component of soil that contributes to its structure and ability to retain water and nutrients, and provides a habitat for soil organisms. In addition, soils play an important role in the carbon cycle by absorbing carbon dioxide from the atmosphere and storing it in organic form (Trojanowski 1973).

Another function of soil is to **provide a habitat for the organisms living in the soil**. Soils are home to a huge variety of organisms, such as bacteria, fungi, protozoa, nematodes, insects, earthworms and many others. These organisms play a key role in soil processes, such as organic matter decomposition, nutrient conversion, nitrogen cycling and many others. Through their activity, they help to maintain the balance of the soil ecosystem and the availability of nutrients for plants (Karczewska 2012).

Soil plays a crucial role in buffering and protecting the environment against various forms of degradation and pollution. It acts as a sink for toxic chemicals and greenhouse gases, improving human and ecosystem health (Hettiarachchi et al. 2023). Soil contributes to planetary health by regulating the carbon pool, providing habitat for biodiversity, and cycling nutrients essential for terrestrial systems (Kopittke et al. 2024). Additionally, soil functions include nutrient cycling, water regulation, and transformation of harmful elements, all vital for sustainable plant biomass production and food security (Frazão et al. 2023). Soil's multifunctional nature allows it to filter chemicals, adsorb pollutants, and mitigate non-point source pollution, such as agricultural runoff, thus safeguarding water quality and reducing environmental risks (Cioruța, Coman 2022). Furthermore, soil protection is essential for conserving natural resources like rocks and underground water, highlighting its pivotal role in maintaining ecosystem balance and human well-being.

Soil plays a crucial protective role in ecosystems by serving as a sink for toxic chemicals and greenhouse gases, thus improving human and ecosystem health (Hettiarachchi et al. 2023). It acts as a natural domain for carbon and plant nutrient cycling, essential for maintaining soil health and ecosystem balance (Woollen 2022). Additionally, soil harbors a variety of micro and macroorganisms that aid in the decomposition of dead plants, releasing essential nutrients vital for plant, animal, and human life, ultimately enhancing soil quality and ecosystem services (Tarafdar 2022). Furthermore, the microbial activity in soil is integral for maintaining ecological balance with minimal environmental impact, contributing to soil health, nutrient cycling, water quality, and productivity management (Raj et al. 2019). Overall, soil's multifaceted functions, from sequestering carbon to supporting microbial diversity, underscore its critical role in safeguarding the health and balance of the environment. Here are some specific aspects of the soil's protective function:

Soil erosion:

Soil acts as a protective layer that prevents soil erosion, which is the process of removing and moving soil particles due to wind, water or human activity. Through its structure, density, organic components and vegetation, soil holds the topsoil layer in place and protects it from humus loss.

Water retention:

Soil has the ability to retain water, which helps to regulate the availability of water for plants and underground water resources. It acts as a natural reservoir that stores water after rainfall or snow melt, and then gradually releases it for plants and water resources, preventing excessive leaching and soil drainage.

Filtration and purification:

Soil acts as a natural filter that retains and filters chemical pollutants such as toxic substances, heavy metals or organic compounds. The physical, chemical and biological processes in the soil help to reduce and neutralise these substances, improving groundwater quality and protecting against environmental pollution.

Nutrient cycle:

Soil plays a key role in the cycle of nutrients, such as nitrogen, phosphorus and potassium. It also acts as a reservoir for these nutrients, supplying them to the plants in adequate quantities, and contributes to nutrient conversion and recycling processes, thereby helping to maintain the ecological balance.

Neutralisation of toxins:

Soil is able to neutralise and break down toxins and chemical compounds that can negatively affect plant, animal and human health. Biological processes in soil, such as biodegradation and biotransformation, can reduce the toxicity of chemicals, facilitating the protection of ecosystems and public health.

All of these soil protection functions are extremely important for maintaining the balance of ecosystems, ensuring agricultural productivity, protecting water resources and minimising the negative impact of human activities on the environment. Protecting the soil and maintaining its health are therefore integral to sustainable environmental management.

In conclusion, the functions of soil in the ecosystem are extremely important for maintaining a healthy and sustainable environment. Soil provides nutrients for plants, stores water, has a role to play in organic matter cycles, provides a habitat for soil organisms and has a protective and buffering function. Understanding these functions is key to optimal soil management and preservation, as a valuable resource for our planet.

1.4. IMPACT OF SOIL ON CLIMATE CHANGE AND SUSTAINABLE DEVELOPMENT

Soil plays an important role in the context of global climate change. Both as a source of emissions and as a storehouse for various greenhouse gases, soil influences the climate balance of our planet. Understanding this impact is the key to developing strategies to reduce greenhouse gas emissions and adapt to changing climate conditions (Banwart et al. 2017).

The soil plays a crucial role in the carbon cycle, acting as a significant reservoir of organic carbon that is exchanged through various biological processes (Duborgel et al. 2023; Prakash, Shimrah 2023; Wang et al. 2023). Human activities like inappropriate agricultural practices, deforestation, and land use changes can disrupt this cycle, leading to the release of carbon from the soil into the atmosphere as carbon dioxide, contributing to climate change (Bertini, Azevedo 2022). Soil erosion, influenced by climate factors like temperature, can further impact the dynamics of soil organic carbon, affecting its mineralization rate and subsequent release of carbon into the atmosphere (Wang et al. 2022). Therefore, understanding and managing soil processes are essential to mitigate carbon losses from the soil and their implications for climate change, emphasizing the intricate relationship between soil, carbon cycling, and climate dynamics.

On the one hand, climate change significantly impacts soil health and functionality. As temperatures rise, soil degradation and erosion intensify, leading to the loss of organic matter (Rocci, Cotrufo 2023). Changes in precipitation patterns under climate change can result in droughts or heavy rainfall, affecting soil structure, water retention, and nutrient availability for plants (Wang et al. 2023; Gregory 2023). Furthermore, climate change alters the distribution and activity of soil organisms, impacting crucial soil processes like organic matter decomposition and nutrient cycling (Jha et al. 2023). However, soil can act as a carbon sink, aiding in greenhouse gas mitigation through carbon retention processes (McDermid et al. 2022). Increasing soil organic matter through practices like conservation agriculture, no-till, or agroforestry can enhance soil organic carbon storage, offering a solution to mitigate the negative impacts of climate change on soil health and promoting sustainable land management practices.

Soil water retention capacity plays a crucial role in mitigating the impacts of climate change on agriculture. Research indicates that soil with good structure and high water retention capacity can help alleviate the effects of drought and decrease the reliance on artificial irrigation (Swami 2023; Zhou et al. 2023; Vogelbacher et al. 2023). By maintaining soil aggregation and enhancing bio-porosity, such soils reduce surface runoff and increase infiltration, contributing to improved water regulation functions (Blanchy et al. 2023). Additionally, adopting soil and crop management practices that conserve or enhance soil structure is essential for sustainable agriculture adaptation to climate change, as it supports agricultural production amidst increasing drought conditions without compromising environmental quality. Therefore, focusing on enhancing soil water retention capacity through appropriate management practices is vital for building resilience in agriculture against the challenges posed by climate change.

Understanding the impact of soil on climate change is key to taking action to manage soil sustainably. Research synthesized from multiple meta-analyses emphasizes the significance of organic soil amendments and continuous living cover in enhancing water regulation functions, reducing surface runoff (Sobieraj et al. 2022), and increasing infiltration (Blanchy et al. 2023). While these practices offer benefits, such as decreased nitrate leaching and greenhouse gas emissions, reducing tillage intensity presents trade-offs like yield penalties and increased greenhouse gas emissions, highlighting the complexity of soil management strategies in climate change adaptation.

Soils play a crucial role in achieving sustainable development goals by contributing to agriculture, the water cycle, land use, poverty alleviation, climate change mitigation, and biodiversity support, making them central to the UN Agenda's objectives by 2030 (Kopittke et al. 2024; Bouma, Veerman 2022). The multifunctional nature of healthy soils, as defined by their ability to sustain ecosystems, enhance water and air quality, support biodiversity, and control nutrient availability, underscores their significance in ensuring human and planetary health. The EU Mission Board for Soil Health and Food has identified specific indicators for soil health, emphasizing the need for integrated assessments to guide sustainable soil management practices and achieve the outlined goals. Therefore, addressing soil health directly impacts the success of sustainable development initiatives, highlighting the critical importance of prioritizing soil health in global agendas to secure a sustainable future.

Poverty, food insecurity and malnutrition, environmental pollution, climate change, natural resource degradation, biodiversity loss and population growth are just some of the global societal challenges underlying the Sustainable Development Goals.

Goal 2: Zero hunger

The aim is to eradicate hunger and improve nutrition by promoting sustainable agriculture. As the basis for more than 95% of global food production, the sustainable use of soil is crucial.

Goal 3: Good health and well-being

The aim is to improve people's health. In addition to concerns about the overexploitation of soils and the loss of essential minerals, this target includes the specific objective of reducing deaths and disease resulting from soil contamination.

Goal 15: Life on land

Efforts to reduce and degrade land fall under Goal 15, which aims to combat desertification, restore degraded land and soils (including land affected by desertification, drought and floods) and work towards a land degradation-neutral world. We cannot afford to lose more uncultivated land if we want to have enough food for a growing world population.

It is also clear that the provision of ecosystem services, in which soil properties and functions play a key role, is very important:

Goal 1: No poverty - healthy, fertile soils underpin agriculture and support the rural economy.

Goal 6: Clean water and sanitation - the filtering and buffering capacity of soil protects water resources from pollution.

Goal 11: Sustainable cities and communities - soil is at the heart of the forest infrastructure that supports sustainable cities through soil cooling, storm water management, increased biodiversity, better air quality and improved mental wellbeing.

Goal 13: Climate action - soil is the world's largest carbon sink and can help mitigate climate change by storing carbon in the soil and reducing greenhouse gas emissions.

SOIL ORGANIC MATTER

Soil organic matter is referred to as the diverse material of organic origin that undergoes varying degrees of processing and degradation in soils. As a non-renewable resource, soil forms the basis of ecosystems and, most importantly, performs many key environmental, social and economic functions. The most important of these are food production (99%), nutrient and water cycling, macro- and micro-nutrient storage, filtration, buffering, biological habitat, raw material sources, climate regulation, legacy, a platform for human-implemented economic structure (Blum 2005; Dominati et al. 2010; Banwart et al. 2017; Allison 1973). A particular function of soil is its role of cleaning up various contaminants from different sources and its contribution to the landscape (Rawls et al. 2003; Keesstra et al. 2012). Soil organic matter is important in the performance of these functions by soils (Craswell, Lefroy 2001; Schmidt et al. 2011). The organic matter content of soils is in continuous decline, as indicated by the European Union's Soil Thematic Strategy (EPA 2024). During the second half of the 19th century, a decline in soil organic matter was recorded from 108 to 188 PgC, mainly from terrestrial biomass (Zech et al. 1997; Lal 2004; Houghton 2012). Soil carbon losses can be mitigated by enriching soils with organic matter and appropriate management (Lorenz, Lal 2012).

Soil organic matter (SOM) is a crucial component for maintaining soil health and fertility while ensuring sustainable environmental functioning. It comprises dead plant debris, roots, and organic matter from soil organisms like dead organisms, animal faeces, and microbial remains, forming a complex mixture rich in carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), sulphur (S), and other elements. This intricate composition results from biochemical processes where plant and soil organism synthesised substances undergo decomposition and transformation within the soil (Doley et al. 2020; Bashir et al. 2021; Paul et al. 2015). The dynamic nature of soil organic carbon (SOC) highlights its pivotal role in ecosystem services and sustainability, with its continuous processing by microorganisms contributing significantly to the benefits derived from ecosystems. Additionally, the presence of soil organic matter influences soil physical, chemical, and biological properties, impacting soil structure, water retention, nutrient availability, microbial populations, and nutrient release, all of which are essential for ecosystem productivity and health.

2.1. SOURCES OF ORGANIC MATTER IN SOILS

The sources of organic matter in soils encompass plant residues, substances from animal organisms, atmospheric agents, and soil microorganisms (Qu et al. 2022; Merkle 1917; Biswas, Kole 2017). These organic materials undergo degradation, decomposition, and transformation processes that are crucial for sustaining soil health and fertility by enhancing nutrient availability, improving soil structure, and preserving soil retention capacity (Zhang et al. 2018). SOM is a key component that influences various biogeochemical processes and carbon-climate feedbacks, with emerging models highlighting the importance of microbial residues in stable SOM formation (Kallenbach et al. 2016). Microbial residues, derived from soil microbes processing plant remnants, contribute significantly to the accumulation of stable SOM, showcasing the pivotal role of soil microorganisms in SOM production and stabilization. Additionally, microbial controls over processes like priming effects and microbial-mediated transformations are essential factors influencing soil carbon dynamics and organic matter turnover in different soil horizons.

Plant residues play a crucial role as a significant source of organic matter in soils, containing a diverse array of organic compounds like carbohydrates, proteins, lipids, lignin, and other polymers (Qu et al. 2022). Through decomposition facilitated by soil microorganisms, these plant residues contribute to the formation of humus, enriching the soil with essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients that become available for plant uptake (Zheng et al. 2021). Studies have shown that different types of plant residues exhibit varying rates of decomposition, with poorly decomposable residues contributing to particulate organic matter in the soil, while highly decomposable residues are a major source of microbial biomass, further emphasizing their role in soil organic matter dynamics (Semenov et al. 2019). Additionally, the fate of microbial-derived carbon from plant residues is influenced by soil properties and management practices, highlighting the intricate relationship between substrate quality and microbial utilization in different soil types (Semenov et al. 2020).

Animal faeces, dead organisms, and other animal residues are significant sources of organic matter in soils, contributing to the nutrient cycling process. Animal manure, rich in nutrients like nitrogen, phosphorus, and potassium, releases these elements into the soil during decomposition (Brichi et al. 2023). Dead organisms, including carrion and animal remains, also play a crucial role in nutrient circulation within soils (Aljumaily, Al-Hamandi 2022). The degradation and decomposition of these organic materials are primarily facilitated by soil microorganisms such as bacteria and fungi, which are essential in converting organic matter into more stable forms (Sun, Ge 2021). These processes highlight the intricate relationship between animal-derived organic matter, nutrient availability, and the vital role of soil microorganisms in maintaining soil health and fertility.

Atmospheric factors play a crucial role in supplying organic matter to soils. Rainwater acts as a significant transporter of organic matter, carrying dissolved organic carbon (DOC) from various sources into soils (Noskova et al. 2022; Liptzin et al. 2022; Xu et al. 2022). Additionally, wind can transport organic dust and fine particles that settle on the soil surface, contributing to the organic matter input (Hong et al. 2022). Moreover, atmospheric microorganisms like airborne bacteria and fungi can serve as sources of organic matter for soil processes, further enriching the soil with organic material (Smreczak, Ukalska-Jaruga 2021). These findings highlight the diverse ways in which atmospheric processes, including rainfall, wind, and microorganisms, influence the supply of organic matter to soils, emphasizing the interconnectedness between the atmosphere and soil ecosystems.

2.2. ORGANIC MATTER CONTENT

The organic matter content of soils refers to the amount of organic matter present per unit volume of soil. This is a key indicator that provides information on the quantity and quality of organic matter that affects soil properties and function.

Factors affecting organic matter content: The organic matter content of soils, as previously mentioned, is influenced by various factors, including soil type. Soil type can have a significant impact on organic matter content. Here are some related factors:

Soil mineral composition: Soils with higher aluminium content and quantitative clay fractions tend to have higher organic matter retention. In comparison, sandy soils may have a lower capacity to retain organic matter.

Soil structure: Soil structure, such as aggregation, porosity and degree of crumbling, can affect organic matter retention. A well-formed soil structure can provide the right conditions for microbial growth and organic matter retention.

Soil reaction: The organic matter content can vary depending on the pH of the soil. For example, acidic soils may have a lower organic matter content, while neutral or slightly alkaline soils may be more conducive to the presence of organic matter.

Land use: The way that land is used, such as cultivation, fertilisation, use of agrochemicals and agricultural practices, can affect the organic matter content of the soil. Intensive cultivation, monocultures and the application of large quantities of mineral fertilisers can lead to a depletion of soil organic matter.

Climate: The climate influences the rate of decomposition of organic matter. In warm and humid climates, decomposition processes tend to be more intensive, which can lead to a more rapid loss of organic matter from the soil.

Anthropogenic factors: Anthropogenic factors, such as soil erosion, environmental pollution and the use of soil for other purposes (e.g. urbanisation), can lead to a loss of soil organic matter.

The variability of the organic matter content of soils depends on many factors, and thorough research and analysis is essential to understanding these relationships. It is also important to take into account the local soil conditions and context, using scientific studies and publications to obtain more complete and accurate information on the organic matter content of soils of different types.

As mentioned above, the organic matter content in soils varies significantly depending on soil type and land use practices. Podzolic and brown soils typically exhibit organic matter content ranging between 1-1.5%, while chernozem and black earths show higher levels at 3-4% (Когут et al. 2023; Bresilla et al. 2023). Meadow, under-pasture, and forest soils contain notably higher amounts of organic matter compared to arable soils (Thai et al. 2021). Factors such as soil parent material, texture, and land use play crucial roles in determining soil organic carbon (SOC) levels, with interactions between these factors influencing SOC accumulation differently across regions (Ortner et al. 2022). Various management practices, including returning crop residues, adding manures, and incorporating pasture rotations, can help increase organic matter content in arable soils, albeit often not fully restoring pre-clearance levels (Powlson et al. 2022) Despite the small amount of organic matter in soils, its specific nature plays a major role in soil-forming processes and in determining soil fertility (Janssens et al. 2005; Kalbitz et al. 2000).

The carbon present in soil organic matter is an important source of this element throughout its cycle. The organic carbon content of soils is 30.1 x 10^{14} kg and is higher than that of all other surface water bodies, which is 20.8 x 10^{14} kg. The largest amounts of CO_2 are emitted into the atmosphere as a result of the decomposition of soil organic matter (Kalembasa, Tengler 1992).

As previously mentioned, the organic matter content of the different soil types varies, as evidenced by the varying content of total organic carbon (OC) in the humus horizons and the carbon ratio values of the humic acid fraction compared to the carbon of the fulvic acid fraction (Ckh:Ckf), as shown in Table 3.

Table 3. Corg (OC) content and Ckh ratio values: Ckf in some soil types in Poland.

Soil type	Corg (OC)	Ckh : Ckf
Chernozems	1.8-2.5	1.4-2.8
Black earth	1.1-3.2	1.5-2.1
Rendsina (Rendzinas)	1.2-3.7	1.2-1.8
Brown	0.8-1.5	1.0-2.2
Fen soils	0.6-3.5	0.5-1.0
Fawn soils	0.7-1.3	1.0-1.3

Source: based on Gonet (1997); Note: Ckh – carbon content in the humic acid fraction of soil organic matter, and Ckf – carbon content in the fulvic acid fraction of soil organic matter.

The organic matter content of the topsoil is also related to the management method. Soil tillage, mainly the change from pasture to arable land, is estimated to lead to significant losses of organic carbon in the overall balance (up to 50 Pg, i.e. 50 x 10^{12} kg) (Janzen 2006). Changes in the total organic carbon content of soils as a result of agricultural use are summarised in Figure 16.

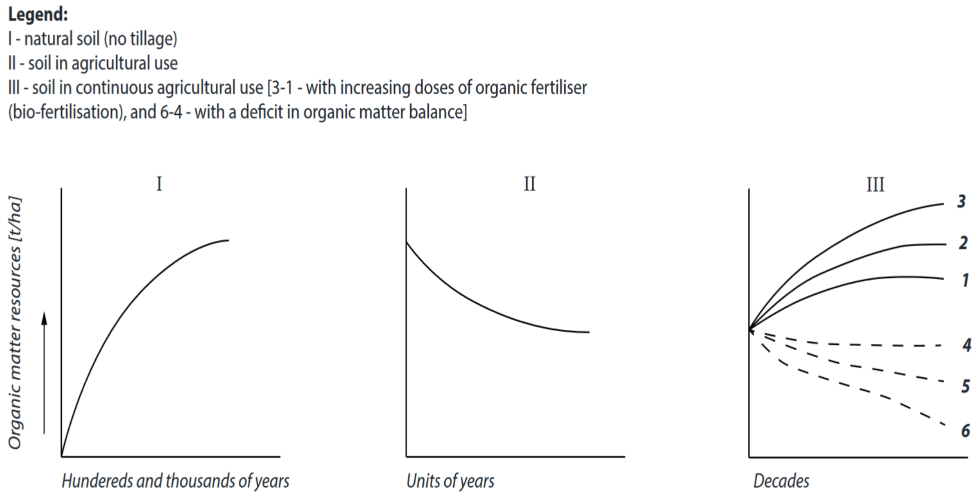

Figure 16. Changes in humus content in agrocenoses depending on the type of soil use.

Source: own elaboration based on Mineev et al. (1993).

In the process of soil genesis, the formation of a humus horizon where organic matter accumulates is a crucial aspect influenced by factors like land cover, environmental conditions, and soil properties (Sokol et al. 2019). Natural forest ecosystems exhibit an accumulation of organic matter due to primary plant succession until reaching an equilibrium state where the soil's organic carbon content peaks, reflecting the soil type characteristics (da Silva et al. 2023). This equilibrium state, often referred to as 'natural' or 'ecological', signifies a dynamic balance between the inflow and mineralization of organic matter, maintaining maximum soil organic carbon levels (Lasota et al. 2020). The presence of a humus horizon in forest soils is indicative of this equilibrium, where the continuous input and decomposition of organic matter reach a harmonious balance, highlighting the importance of organic matter dynamics in maintaining soil health and stability (Álvarez-Romero et al. 2015).

The agricultural use of soils leads to a dramatic reduction in the organic matter content. A new level of organic matter is then established, significantly lower than the 'natural' level. The decrease in organic matter content is explained by its intensive mineralisation. This process occurs due to agro-technical treatments, particularly ploughing, and a low supply of fresh organic matter in the form of crop residues. The bulk of the biomass produced is lifted from the ecosystem in the form of a usable crop (Bellamy et al. 2005).

Under conditions of intensified crop production, changes in soil organic matter content can vary, with absolute variations in Corg (OC) content generally not exceeding 1% (Скрильник et al. 2020; Garratt et al. 2018). Mineral fertilisation alone, at rates meeting plant nutritional needs, typically results in slight fluctuations in Corg (OC) content (Skrylnyk et al. 2021). Conversely, optimal organic fertilisation leads to a more substantial increase in humus content in the arable layer (Balík et al. 2020). Application of organic fertilisers in 'melioration' doses can even yield a significant boost in humus reserves (Xu et al. 2017). However, under conditions of progressive erosion or other soil degrading factors, a notable reduction in Corg (OC) content can occur. These findings underscore the critical role of fertilisation practices and environmental factors in influencing soil organic matter dynamics in agricultural systems.

The humus content and quality of soils are also determined by the type of shifts, which is linked to the quantity and quality of post-harvest residues left in the field. Humus-forming plants, i.e. plants that enrich soils with organic matter, include grasses and butterfly plants. Slightly smaller amounts of post-harvest residues are contributed to soils by cereals, and to a lesser extent, by root crops. Table 4 summarises the results obtained from long-term experiments, conducted over a period of more than 100 years. They show the effect of the type of fertilisation on the organic carbon content of soils. These results confirm the role of organic-mineral fertilisation, which typically enriches soils in humus, but deprives them of humus during cultivation.

Table 4. Effect of multi-year fertilization on soil properties based on multi-year experiments with vegetables.

Fertilisation* since 1923	pH	Corg (OC)	Content [mg/kg soil]							
			N	P	K	Ca	Mg	Cu	Mn	Zn
manure 20	6.3	0.97	934	441	605	909	459	8.5	96	26
manure 40	6.4	1.13	1054	531	743	1282	511	9.6	111	31
manure 60	6.0	1.40	1229	572	909	1677	601	11	128	37
manure 20 + 2 NPK	6.5	0.87	872	559	787	940	458	10.1	125	28
manure 40 + 2 NPK	5.0	1.13	999	614	873	1203	501	9.1	130	34
manure 60 + 2 NPK	5.0	1.55	1221	720	831	1442	502	10	130	37
1 NPK	5.8	0.54	668	438	623	813	428	9.9	99	29
2 NPK	5.3	0.40	697	486	583	500	447	9.5	117	25
3 NPK	5.0	0.40	799	450	727	485	309	0.0	96	35

Source: own elaboration based on Mercik (1994).

Note: * Fertilization per hectare in each year: I) manure application at rates of 20 t/ha, 40 t/ha, and 60 t/ha, as well as manure at rates of 20, 40, and 60 t/ha enriched with NPK (nitrogen, phosphorus, potassium) doses, resulted in an increase of organic carbon in soils, whereas fertilization; II) exclusively with mineral NPK fertilizers at rates of presented below:

manure	20 t/ha	40 t/ha	60 t/ha
1 NPK	75 kg N	50 kg P_2O_5	100 kg K_2O
2 NPK	150 kg N	100 kg P_2O_5	200 kg K_2O
3 NPK	225 kg N	150 kg P_2O_5	300 kg K_2O

caused a decrease in organic carbon content in soils (as shown in Table 4).

The properties of humus substances are just as important as the amount of humus in soils. As a general rule, the introduced post-harvest residues cause a decrease in the carbon and oxygen content of the humic acid molecules, a decrease in the value of the degree of internal oxidation, and a change in the spectrophotometric and thermal parameters (Gonet, Debska 1998). However, the transformation directions of organic material freshly introduced into the soil are largely determined by its chemical composition, mainly the value of the C ratio: N and content of readily degradable compounds.

Plants exhibit significant variations in their quantitative composition despite containing similar groups of compounds. Maize post-harvest residues are distinguished by a high proportion of hemicelluloses and starch (approximately 42%) (Reynolds et al. 2005), while alfalfa residues are characterized by proteins (around 16%) (Mohammed et al. 2013), and wheat residues predominantly consist of cellulose (about 42%) (Mohammed et al. 2013). These differences highlight the diverse biochemical compositions of plant residues, showcasing the unique distribution of key components such as hemicelluloses, starch, proteins, and cellulose in maize, alfalfa, and wheat residues. Understanding these variations is crucial for various applications, including agriculture, nutrition, and biofuel production, emphasizing the importance of studying and utilizing the distinct compositions of plant residues for different purposes.

The properties of humus substances are significantly influenced by the type of fertilisation (Gonet, Wegner 1990). Manure fertilisation has been shown to aliphatise soil humic acids, increase their susceptibility to oxidation, alter their optical properties and reduce their heat of combustion and thermal decomposition activation energy values. The humic acids of soils fertilised solely with mineral fertilisers are characterised by a higher proportion of aromatic structures and are less susceptible to oxidation than soils fertilised with organic fertilisers.

2.3. FUNCTIONS OF ORGANIC MATTER IN THE FORMATION OF SOIL PROPERTIES

SOM is a crucial component in soil ecosystems, impacting various aspects such as soil structure, water retention, nutrient availability, pH regulation, pollutant binding, detoxification, and SOM preservation. SOM improves soil physical, chemical, and biological properties, enhancing soil sustainability and productivity. It plays a role in maintaining soil structure, increasing water-holding capacity, providing essential nutrients, reducing aluminum toxicity, and promoting microbial activity. Additionally, SOM aids in pollutant binding and detoxification, regulates soil pH, and contributes to long-term soil organic matter preservation. Various mechanisms, including nutrient mineralization, microbial interactions, and organic matter decomposition, underlie the benefits of SOM, highlighting its significance in soil health and ecosystem functioning (Doley et al. 2020; Voltr et al. 2021; Qu et al. 2022; Fageria 2012).

The key functions of organic matter in determining soil properties include:

- **Improving soil structure:**

Organic matter acts as a binder, forming soil aggregates that improve soil structure. Aggregates provide greater water permeability, better soil ventilation and a looser structure, facilitating plant root growth and root penetration.

- **Increasing water retention capacity:**

Organic matter is able to retain water in soils. Organic matter retains and stores water, which is particularly important during periods of drought, ensuring that plants have access to water in difficult conditions. At the same time, in the event of heavy rainfall, the organic matter helps to maintain the water balance by retaining excess water and preventing erosion.

- **Nutrient supply:**

Organic matter acts as a reservoir of nutrients in soils. It contains macronutrients, such as nitrogen, phosphorus and potassium, as well as micronutrients that are released by the decomposition processes of organic matter. These nutrients become available to plants, providing them with the necessary substances for growth and development.

- **Soil pH regulation:**

Organic matter acts as a buffer, regulating the pH of soils. Organic substances maintain optimum pH values for plant growth, both by reducing soil acidity and reducing alkalinity. This allows plants to take up nutrients efficiently and avoid the stress caused by improper pH.

- **Binding and detoxification of pollutants:**

Soil organic matter can bind and detoxify various pollutants. Organic substances form chemical complexes with heavy metals, pesticides and other organic compounds, reducing their toxicity and decreasing their mobility in soils. This action helps to protect both the soil environment and plant health.

- **Preservation and retention of organic matter:**

Organic matter can survive in soils for a long time. Stable organic matter decomposes slowly, releasing nutrients gradually and providing sustainable organic matter retention. This process helps to maintain the beneficial properties of soils over a longer period.

- **The impact of organic matter on CO_2 sequestration**

CO_2 sequestration is the process of preventing large amounts of carbon dioxide (CO_2) from being emitted into the atmosphere from point sources of pollution (Freibauer et al. 2004), such as power plants and heavy industry factories. The process consists in capturing CO_2 from the flue gas stream, transporting it and injecting it into a selected storage site. Geological sequestration of CO_2 is the safe storage of CO_2 emissions from the combustion of fossil fuels in industrial installations, in deep geological formations and structures, for hundreds and thousands of years. According to a study by Freibauer et al. (2004), the potential for CO_2 absorption per ha in European agricultural soils by 2008-2012 for a business-as-usual scenario is very significant. Realistically, agricultural soils in the European Union can sequester up to 16-19 Mt C per year.

Soil C sequestration and low-carbon technologies have also been proposed as a strategy to mitigate the effects of greenhouse gas emissions into the atmosphere (Lal 2001; Janzen 2006; Minasny et al. 2017).

Research into the impact of organic matter on carbon dioxide (CO_2) sequestration in soils is relevant to climate change and sustainable agriculture. Here are some tests that can be carried out to assess the impact of organic matter on soil CO_2 sequestration:

To assess the impact of organic matter on soil CO_2 sequestration, the injection test can be conducted by adding varying amounts of organic matter to soil samples and monitoring CO_2 emissions during decomposition (Duan et al. 2023; Zhang et al. 2023). This test involves placing soil samples in airtight containers and introducing organic materials like compost, manure, or plant residues. The emitted CO_2 is then measured over a specific period to evaluate the effect of organic matter on sequestering CO_2. Studies have shown that the addition of organic materials, particularly litter, stimulates soil organic carbon (SOC) mineralization and decomposition, enhancing CO_2 release (Zhang et al. 2023; Debska et al. 2022). Additionally, the injection test can help understand the priming effect of organic matter on SOC and its interactions with soil microbial diversity, providing insights into carbon sequestration dynamics in soils.

Microbiological test: This test assesses the activity of soil microorganisms responsible for the decomposition of organic matter and CO_2 emissions. Soil samples with different levels of organic matter are incubated under controlled laboratory conditions and CO_2 emissions are then monitored using techniques such as gas chromatography. Scientific studies provide valuable insights into assessing soil microorganism activity and CO_2 emissions related to organic matter decomposition. Research has shown that soil microbial biomass C can be accurately estimated using fumigation-incubation methods, highlighting the importance of controlling variables like temperature and moisture in laboratory settings (Wu et al. 1996; Herath et al. 2015). Additionally, experiments comparing the decomposition of biochar and fresh organic matter have demonstrated the potential of biochar to sequester carbon and influence native soil organic matter cycling, emphasizing the need for further investigations into these processes (Palmer et al. 2019). Models incorporating microbial biomass activity have successfully simulated priming effects on soil organic matter decomposition, showcasing the significance of considering microbial dynamics in understanding carbon and nitrogen turnover in soil systems (Jones et al. 2000). By incubating soil samples with varying organic matter levels and monitoring CO_2 emissions, researchers can gain valuable insights into how different organic matter types and quantities impact microbial activity and CO_2 sequestration processes.

Testing in the field: Field experiments play a crucial role in evaluating the impact of organic matter on CO_2 sequestration at a larger scale. Studies like those by Leifeld and Fuhrer (2010) have shown that organic farming practices can influence soil organic carbon dynamics. Robertson et al. (2015) emphasize the importance of long-term field experiments to understand the effects of conservation management practices on soil organic carbon stocks. Additionally, Herath et al. (2015) highlight the significance of comparing the decomposition of biochar to original feedstock to determine net carbon sequestration potential. Qian and Follett's (2002) research underscores the substantial contributions of turfgrass to sequestering atmospheric carbon, with historic data indicating significant soil organic matter responses to decades of turfgrass culture. By setting up experimental fields with various organic fertilization practices and monitoring soil CO_2 emissions over time, as suggested in the question, valuable insights can be gained into the dynamics of carbon sequestration in different soil types and management systems (Robertson et al. 2015; Herath et al. 2015).

The results of these tests can provide information on the impact of organic matter on CO_2 sequestration processes in soils. Increased organic matter content can lead to increased CO_2 sequestration through increased production of organic matter, increased microbial activity and improved soil structure. This is important in the context of the fight against climate change, as the greater the amount of carbon dioxide stored in soils, the lower its concentration in the atmosphere.

As inferred from the above considerations, SOM plays a crucial role in maintaining soil health and supporting sustainable soil ecosystems by influencing various key properties. It enhances soil structure, water retention capacity, nutrient availability, pH regulation, contaminant binding, detoxification capacity, and persistence, as highlighted in the literature (Ros et al. 2023; Brichi et al. 2023). The inclusion of organic residues like compost, animal manure, and crop residues enriches soil health, positively impacting crop productivity while also improving soil physical, chemical, and biological attributes. Moreover, SOM, particularly humic substances, detoxifies harmful substances in soil, increases nutrient availability, and contributes to greenhouse gas emission reduction. Understanding the multifaceted functions of organic matter is essential for informed decision-making in soil management, agriculture, and environmental protection to ensure the long-term sustainability and efficiency of ecological processes within soils.

2.4. HUMUS AND ITS ECOLOGICAL SIGNIFICANCE

Humus, a crucial component of soil ecosystems, is a highly decomposed organic material formed through biological processes like the breakdown of plant and animal residues by decomposing microorganisms (Kozlova et al. 2023; Amaya et al. 2022). It consists of humic substances that positively impact soil quality and fertility by enhancing water retention, stabilizing soil structure, promoting microbial activity, and influencing plant physiology and nutrient uptake (Savich et al. 2001). Humus is essential for sustaining the soil ecosystem by providing nutrients for plant growth and maintaining soil fertility (Vikram et al. 2022). The composition and properties of humus vary depending on the soil type and environmental factors, with different humus fractions contributing to soil fertility and crop yields (Aparin et al. 2018). Understanding the significance of humus in soil ecosystems is crucial as it represents an advanced stage of decomposed organic matter with increased stability compared to less-decomposed plant residues, highlighting its vital role in soil health and functioning.

Soil humus is very important for soil quality and the functioning of soil ecosystems. It has many beneficial properties, such as the ability to retain water and nutrients, improve soil structure, regulate soil pH and support biological processes. Humus acts as a 'storehouse' of nutrients and organic substances that are gradually released during biological processes, providing nutrients to plants and contributing to healthy plant growth.

Assessing the humus content of soils is essential to evaluate their quality and ability to sustain agricultural yields, as well as in the context of environmental protection and sustainable management of soil resources.

In nature, plants and animals die and leave behind organic matter, such as leaves, branches, dead roots, litter and even animal remains. These organic residues gradually undergo a process of decomposition in soils, leading to the formation of humus. This process is complex and depends on many factors, such as humidity, temperature, soil pH, the presence of micro-organisms and oxygen availability.

Soil microorganisms, including bacteria and fungi, are crucial in the decomposition of organic matter, as supported by various research papers. Bacteria and fungi produce enzymes that facilitate the breakdown of complex organic compounds into simpler components like sugars, amino acids, and fatty acids (Sun, Ge 2021; Zhang et al. 2018). These components are then metabolized by microorganisms, leading to the formation of more stable organic compounds known as humus (Biswas, Kole 2017). Additionally, the decomposition process involving soil invertebrates like earthworms influences substrate chemistry and microbial community dynamics, with a significant correlation between bacterial community composition and dissolved organic matter changes observed during decomposition (Vidal et al. 2021). Furthermore, the microbial mediation of organic inputs and native soil organic matter decomposition, as highlighted in the study using isotopic methods and solid-state NMR, emphasizes the intricate role of microorganisms in soil carbon dynamics and the formation of soil organic matter (Zheng et al. 2023).

Humus is a fundamental component of soil and is characterised by its unique chemical and physical properties. It is more resistant to further decomposition and can survive in soil for long periods. Humus is characterised by its dark brown colour and distinct aroma.

It is worth noting that the process of humus formation is continuous and occurs over many years. The longer organic matter remains in soils, the longer it is subjected to decomposition, leading to an increase in humus. In soils with a high humus content, humus layers can be found with varying degrees of decomposition, from less decomposed to more stable.

The definition of humus as decomposed plant and animal residues that have undergone a decomposition process in soils allows us to understand that humus is not only a product of the natural life cycle, but also a key component of soils that influences their physical, chemical and biological properties.

2.4.1. Humus formation process

The formation of humus in soils is a multifaceted process involving intricate interactions between microorganisms, chemical factors, and physical processes, as supported by various research papers. The decomposition of organic matter into humus is facilitated by beneficial microorganisms like fungi and bacteria present in the soil (Malyk, Pankiv 2020; Savich et al. 2001). Additionally, the properties of humus compounds play a crucial role in its agro-nomic assessment, highlighting the importance of chemical factors in humus formation (Amaya et al. 2022). Moreover, the classification of humus forms is based on morpho-genetic characters, emphasizing the role of soil structure in humus development (Rodrigues et al. 2020). These combined factors, including biological, chemical, and physical processes, work synergistically to transform organic matter into humus, ultimately contributing to soil fertility and the sustainability of the total soil ecosystem.

As previously mentioned, micro-organisms, such as bacteria and fungi, play a key role in the decomposition of organic matter and the formation of humus. Bacteria are responsible for breaking down organic compounds, such as sugars, proteins and fats, with the help of the enzymes they secrete. Meanwhile, fungi are able to break down more complex organic substances, such as cellulose and lignin, thanks to the enzymes they produce. Through this process, micro-organisms convert organic substances into more stable compounds that form humus.

Chemical factors also play an important role in humus formation. Factors such as soil acidity (pH), oxygen, moisture and soil chemistry affect the activity of micro-organisms, and thus, the rate of decomposition of organic matter. For example, the optimum soil pH for most organic matter-degrading microorganisms is around 6-7, and oxygen deficiency can limit their activity.

Physical processes also have a significant impact on humus formation. Micro-organisms function most effectively in soils in good physical conditions, that is, when soil texture, water permeability and pore presence are adequate. Thanks to the well-developed soil structure and the presence of pores, micro-organisms have access to organic matter and oxygen, which stimulates the decomposition process.

It is worth noting that the rate of humus formation depends on many factors, such as the type of organic matter, soil moisture, temperature, pH, the presence of micro-organisms and the activity of soil fauna. For example, in soils found in warm and humid climates, the humus formation process can be more intense than in dry and cool conditions.

Understanding the biological, chemical and physical processes that lead to humus formation in soils helps us to understand the importance of this process for soil and ecosystem health. It is important to remember that humus plays a significant role in enhancing soil quality and sustainable soil management (Maciejewska et al. 2024). It improves soil structure, increases soil water and nutrient storage capacity, regulates soil pH, and binds and detoxifies contaminants, as supported by various research papers. The molecular structure of humic substances, characterized by weak dispersive forces and hydrogen bonds, contributes to soil physical and chemical quality (Amaya et al. 2022). Long-term fertilization impacts the composition and structure of humic substances, with organic treatments leading to more aliphatic nature and increased carbon content, indicating sustainable crop management practices (Ahamadou et al. 2022). Additionally, the combined use of humic preparations and pesticides influences the quantitative composition of carbohydrates in soil aggregates, reducing the toxic effects of pesticides and preserving soil structure, highlighting the importance of humic substances in soil health and fertility (Piccolo 2002). Moreover, the dynamics of humus content in agricultural soils demonstrate the stabilization and increase of humus reserves over time, emphasizing the significance of biologization of agriculture for improving soil fertility and humus condition (Lykhman et al. 2020).

As a product of the decomposition of organic matter, humus has a number of unique properties that contribute to its role in improving soil structure and the functioning of entire ecosystems. We will discuss some of these humus characteristics below.

The first noticeable feature of humus is its **dark brown colour.** This colour is due to the presence of organic compounds, such as humus, which are formed by the decomposition processes of organic matter. The dark colour of humus attracts and absorbs solar energy, which can affect soil temperature and biochemical processes.

Another characteristic feature of humus is **its distinctive smell** often described as ‘earthy’ or ‘woodsy’ due to the release of volatile organic compounds during organic matter decomposition (Akhatov et al. 2022). The formation and properties of humus play a crucial role in soil fertility and plant growth (Savich et al. 2001). Studies have shown that humus forms reflect mechanisms of organic matter stabilization and are linked to the soil's capacity to store carbon, highlighting the importance of humus in soil health and nutrient availability (Bonifacio et al. 2011). Additionally, the distribution of humus reserves in brown soils of mountain pastures is uneven and strongly influenced by erosion, impacting the total humus content and soil productivity (Kodama et al. 2008). Therefore, the distinct aroma associated with humus is a result of the complex processes of organic matter decomposition and transformation, contributing to the refreshing atmosphere of soils and forests.

The various types of soil organic matter can be divided into fresh undecomposed plant and animal residues and humus substances. Among humus substances, a distinction is made between non-specific organic matter and specific humus substances.

Non-specific organic substances are chemical compounds with known properties and structures. These include carbohydrates, hydrocarbons, fats, organic acids and their esters, alcohols, amino acids, phenols, pigments, tannins, terpenes and other relatively low molecular weight compounds.

Actual humus substances are a complex of organic compounds ranging from brown to yellow in colour. According to Kononowa (1968), they are divided into:

Fulvic acids - soluble in dilute **acid** and alkali solutions,

Hymatomellanic acids - insoluble in acids, but soluble in alkali solutions and alcohol,

Humic acids - soluble in alkali solutions and alcohol,

Humins - insoluble in acid and alkali solutions.

Soil organic matter undergoes constant microbiological, physical and chemical transformations, including fragmentation by soil microorganisms and subsequent mixing with soil minerals, a process known as mineralisation (Zhang et al. 2018; Vidal et al. 2021). These transformations involve the decomposition of proteins, ammonification, nitrification, and enzymatic breakdown of carbohydrates and pectic compounds by soil microbes, leading to full mineralisation over time (Gregorich et al. 1996). Studies have shown that the formation of mineral-associated organic matter occurs in the vicinity of decaying plant residues, with microbial activity playing a crucial role in the conversion of litter-derived carbon and nitrogen into mineral-associated organic matter, highlighting the importance of microbial processes in soil organic matter dynamics (Karavanova et al. 2019). Additionally, the stability of dissolved organic matter in soil solutions varies across soil horizons, with the content of hydrophobic and phenolic fractions influencing the mineralisation of carbon, indicating the gradual nature of mineralisation processes in soils (Cotrufo et al. 2015).

Butting is a process during which the decomposition of organic compounds takes place under aerobic conditions. Full oxidation products are then formed: CO_2 and H_2O and ions such as SO_4^{2-}, PO_4^{3-}, NO_3^-, etc.

Decay is an anaerobic process that occurs under conditions of excessive moisture or under conditions of oxygen deprivation as a result of excessive growth of soil microorganisms.

The putrefaction process produces CO_2 and H_2O as well as methane, hydrogen sulphide and other compounds.

Further decomposition takes place through biological and chemical transformation, resulting in humification.

Humification is the biochemical process by which humus is formed. It is believed to occur in two stages. The former consists of the decomposition of the organic substrate into compounds of simple chemical structure, while the second involves synthesis by combining simple chemical compounds into proper humus compounds. The process of humification remains poorly understood. There are a number of hypotheses explaining the formation of humus compounds, and therefore, the definition of humus. According to Terlikowski (1956), humus is 'amorphous organic matter resulting from decomposition and synthesis by chemical and biological means', while Martin and Haider (1971) claim that it is a natural product of the biological activity of the soil environment. These authors also state that humus contains various organic substances, the most important of which are polymers from the humic acid group and polysaccharides, which account for about 90% of total soil organic matter. The full definition of the synthesis process of humic substances is still highly controversial. There are many hypotheses in the literature about the formation of humic substances in soils; according to Felbeck (1966), these hypotheses are as follows:

1. **The hypothesis of successive phases** of processing plant material, known as the lignin theory, is supported by various research findings. Studies have shown that microbial metabolism on plant lignin contributes to the formation of humic substances (HSs) in soils, with white-rot fungi and microbial consortia playing key roles in structurally modifying lignin and enhancing plant-stimulatory activities (Rehman et al. 2022). The type of humic substances formed from plant residues is largely determined by the natural characteristics of the plant material. During the first stage of the humification process, high molecular weight humic acids and humins are formed. In turn, these compounds are degraded to fulvic acids and further through the mineralisation process to CO_2 and H_2O. Additionally, the transformation of lignosulfonate into humic-like substances during synthesis of Lignohumate aligns with the concept of successive stages of processing plant material, resulting in the accumulation of humic substances with varying biological activities (Yakimenko et al. 2021). Furthermore, the degradation of lignin by white-rot fungi leads to the formation of HS with aliphatic characteristics, supporting the idea that resistant plant components undergo alterations during humification processes (Khatami 2020). Moreover, the efficient degradation of soil humic acids under cellulolytic conditions highlights the role of enzymes like cellobiose dehydrogenase in the breakdown of aromatic compounds, further emphasizing the successive phases of processing plant material in soil humus formation (Lisov et al. 2020). These findings collectively demonstrate that the type of humic substances formed from plant residues is influenced by the natural characteristics of the plant material and the microbial processes involved in their degradation and transformation in soils (Kögel-Knabner et al. 2003).

2. **The chemical polymerization hypothesis** posits that under microbial influence, plant material degradation leads to the synthesis of phenols and amino acids, which are subsequently oxidized and polymerized in the natural soil environment, ultimately forming humus substances. This process is supported by various studies: one demonstrated the transformation of phenolic substrates into oligomeric products through biosynthetic reactions (Suflita, Bollag 1981), while another highlighted the role of microbial activity in modulating cell-mediated polymerization of monomers (Bennett et al. 2022). Additionally, research on litter decomposition in wetland soils showed that changes in litter protein content paralleled variations in bulk nitrogen content, indicating the influence of microbial processes on nitrogen dynamics and humus formation (Reuter et al. 2020). Furthermore, experiments with mineral horizons confirmed the polymerization of humic substances under the catalytic effect of phenoloxidases, emphasizing the role of biotic catalysts in this process (Zavarzina 2006). These findings collectively suggest that the nature of resulting compounds during humus formation is influenced by microbial activities and enzymatic reactions rather than the type of plant material, supporting the chemical polymerization hypothesis.
3. **The cellular autolysis hypothesis**. The process of cellular autolysis provides evidence supporting the hypothesis that humus compounds are formed by the breakdown of dead microbial and plant cells. Autolysis involves the degradation of cell components, releasing sugars, amino acids, nucleic acid products, and other organic compounds (Monodane et al. 1978; Suzuki et al. 2013; Alexandre 2011; Huang et al. 2021). This breakdown leads to the formation of various organic molecules that can further condense and polymerize through free radical reactions, contributing to the complex composition of humus compounds. Studies on yeast autolysis have shown the degradation of cellular macromolecules and leakage of breakdown products into the extracellular environment, which aligns with the concept of organic compound transformation during autolysis (Hernawan, Fleet 1995). Additionally, observations of autolysis in bacteria have highlighted the hydrolytic degradation of cell wall components, further supporting the generation of organic building blocks for humus formation.
4. The microbial synthesis hypothesis. The microbial synthesis hypothesis posits that microorganisms utilize plant material to produce intracellular high-molecular humus compounds, which are released into soils upon microbial death. This process significantly contributes to soil organic matter (SOM) formation and stability (Mason-Jones et al. 2023). Microbes store a substantial portion of their carbon intake in the form of triacylglycerides (TAGs) and polyhydroxybutyrate (PHB), which can represent a considerable C pool and contribute significantly to biomass growth, even under carbon limitation (Bradford et al. 2013; Kallenbach et al. 2016). Additionally, dissolved plant-derived compounds, such as sugars and amino acids, are essential precursors for stable soil organic carbon formation, with microbial uptake and biosynthesis playing crucial roles in this process (Mason-Jones et al. 2023). Overall, the evidence supports the idea that microorganisms play a vital role in transforming plant material into stable soil organic compounds through microbial synthesis and subsequent release into the soil upon microbial death.

It is difficult to determine which of the above hypotheses is dominant during the formation of humus compounds in soils. It is presumed that all four of these processes occur simultaneously in such areas, but depending on the environmental conditions, the intensity of one of the processes presented may dominate over the others. However, a common feature of these hypotheses is that high molecular weight compounds are formed first, which are degraded most likely by oxidation to form low molecular weight compounds, which then undergo condensation and polymerisation.

The above considerations suggest that soil humus is a mixture of different organic compounds. It is dominated by two types of polymers: polymers of aromatic compounds and polysaccharides. The latter are mainly products of microbial synthesis and can account for up to 30% of humus content (Martin, Haider 1971).

Humified organic substances of an acidic nature, including humic acids, fulvic acids, and humins, are complex mixtures of organic compounds found in soil organic matter (Piccolo 2002; Nissenbaum, Kaplan 1972; López et al. 2008; Da Silva et al. 2018; Eshwar et al. 2017). These fractions exhibit distinct characteristics based on their molecular structures and polymerization levels. Humic acids, for instance, are composed of an aromatic core linked to carbohydrates, proteins, and amino acids, forming spherical colloids with a dispersed structure. Fulvic acids, on the other hand, are soluble in both acid and alkali, while humins are the least soluble fraction, being neither soluble in acid nor alkali. The differences in elemental composition, protonation constants, and acid-base properties further distinguish these humic fractions, highlighting their diverse nature and roles in soil ecosystems.

The active side chain groups in humic acid molecules play a crucial role in determining their interactions with mineral and organic compounds. Research has shown that humic substances contain various active functional groups such as carboxylic (-COOH), hydroxyl (-OH), ketone (>C=O), quinone (>C=O), and methoxy (-OCH3) (Schnitzer, Khan 1972; Piccolo 2002), as shown in Table 5. These functional groups contribute to the redox-active nature of humic acids, influencing their reducing capacities and redox reactions in different environments (Theng 2012). Additionally, the presence of these functional groups, particularly quinone moieties, has been identified as the redox-active centers within humic acids, facilitating electron transfer processes and enhancing microbial reduction of nitrate and FeOOH. The conformational structure of humic substances is also affected by these active groups, with hydrophobic forces predominantly stabilizing their supramolecular associations. These findings highlight the significance of active functional groups in humic acid molecules for their reactivity and interactions with various compounds in the environment.

Table 5. Content of active groups in humic substances extracted from different soils.

Active groups [mmol/g]				
carboxyl (-COOH)	phenolic (-OH)	alcohol (-OH)	ketone (>C=0)	methoxyl (-OCH3)
humic acids				
4.5	2.1	2.8	4.4	0.3
3.0	5.7	3.5	1.8	n.s.
1.5	4.2	2.8	0.9	n.s.
4.7	5.5	0.2	5.2	n.s.
4.7	3.6	n.s.	3.1	0,3
fulvic acids				
8.5	5.7	3.4	1.7	n.o.
9.1	3.3	3.6	3.1	0,5
humins				
3.8	2.1	n.s.	4.8	0.4
2.6	2.4	n.s.	5.7	0.3

Source: own elaboration based on Schnitzer and Khan (1972). Note: n.s. stands for 'not specified'.

Among the organic matter fractions, humic and fulvic acids exhibit the highest reactivity towards mineral and organic soil constituents. The proportion of humic fractions is approximately 40-60% in relation to the content of humified soil organic matter. The degree of binding of various chemical compounds entering the soil is therefore a function of its humic abundance (Skłodowski 1974).

Soil humus has multiple functions in the soil environment. Among the most important are:

- Participation in the formation of soils and determining their properties,
- Participation in the biological cycle of elements,
- Providing nutrient elements for plants and energy and carbon for soil microorganisms,
- Impact on plant growth and development,
- Participation in ion exchange processes,
- Influence on solubility and migration of elements,
- Regulation of soil buffering properties and redox potential,
- Binding of pesticides and inhibition of certain plant pathogens.

One of the most important functions of humus is its protective function. The protective effect of organic matter is explained by its properties. Organic matter is a regulator of nutrient uptake by plants, increases the effectiveness of mineral fertilisers and protects unproductive elements from leaching. Soils with a high organic matter content are biologically active, releasing more CO_2. Humus soils are characterised by better physical properties and water and air conditions. Soil genesis and humus formation processes are largely linked to the climate. Climatic conditions determine both the humus content of soils, as well as the group composition and properties of humus substances (Skłodowski 1974,1994). Schnitzer and Khan (1978) and Orłow (1984) showed that the humic acids of soils in different climatic zones differ in elemental composition, structure and spectrophotometric properties.

2.4.2. Improving the structure and sorption properties of soils

Humus compounds play a very important role in determining soil structure. According to many authors cited by Kononowa (1968), soil aggregates are formed from mineral particles through their fusion with humus substances. The higher the content of these substances in soils, the higher the number of tubercles with a diameter of > 1 mm.

The benefits of the organic matter found in soils are also linked to the positive effect of such substances on the physical properties of soils. This is confirmed by many years of field experiments comparing, among other things, the effectiveness of organic fertilisation and the effects of mineral fertilisation. In a long-term experiment conducted in Skierniewice on light soil, it was found that the higher the organic matter content as a result of systematic manure fertilisation, the higher the proportion of tubercles with a diameter of 1 mm, which was not the case with mineral (NPK) fertilisation. The improvement in soil structure also had a positive effect, increasing water retention capacity, as shown in Table 6. This is also confirmed by the results of other studies (Hurich, Skłodowski 1962).

The products of the transformation of organic matter have a positive effect on the sorption properties of soils, as they have a higher sorption capacity compared to mineral colloids. They are, therefore, an essential component of their sorption complex. The organic part of this complex can absorb 4-12 times more cations than the mineral part. At the same time, exchangeable cations – Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, and others bound by organic fractions – are more easily displaced from them than cations bound by soil mineral colloids. The results of the tests carried out at the experimental sites in Skierniewice, summarised in Table 7, show that the higher the organic matter content, the higher the sorption capacity of soils in relation to exchangeable cations.

Table 6. Effect of differential fertilisation on the structure and capillary water retention capacity of a light soil. Experiments carried out over many years in the Experimental Facility Skierniewice (Poland).

Type of fertiliser and dosages used each year	Content humus* [%]	Grime fraction content** [%]		Capillary water volume [°10]
		1 mm	< 0.25 mm	
Manure, 60 t/ha	2.56	30	41	27.5
Manure, 20 t/ha	1.74	20	49	23.2
NPK 280 kg/ha***	1.10	13	59	16.1

Source: own elaboration based on the study by Jagoda and Skąpski (1966). Note: fertilization doses in kg/ha: nitrogen (N) — 72; phosphorus in the form of P_2O_5 — 66; potassium in the form of K_2O — 130.

Table 7. Effect of varying fertilisation on the sorption capacity of light soil. Experiment carried out over many years in ZD Skierniewice.

Fertiliser types and dosages used each year	Humus content [%]	Exchangeable cation content*: Ca^{2+}, Mg^{2+}, Na^{+} (mgR/100 g soil)	Exchangeable cations [%]			
			Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}
Manure, 60 t/ha	2.60	7.36	79.5	10.6	7.5	2.4
NPK 268 kg/ha	0.95	3.05	74.9	7.5	13.0	4.6

Source: own elaboration based on Maciejewska (1973). Note: * in the sorption complex.

Thanks to their sorption capacity, organic substances strengthen the buffer properties of soils, regulating excessive concentrations of mineral nutrients, and heavy metals entering the soil. The negative effects of the acid reaction are less marked in soils rich in organic substances than in soils lacking in these substances, because they bind the active forms of aluminium, manganese and iron, mitigating their toxic effects (Boguszewski, Gajek 1980). This was confirmed by the results of other experiments in which increasing doses of aluminium were added to turf and podzolic soils with different organic matter contents (Naramabuye, Haynes, 2006). In soils with a low organic matter content, already low doses of aluminium showed a toxic effect, causing a decrease in plant yield, while in soils with a high organic matter content, the same reduction in plant yield was not recorded until considerably higher doses of this element were used.

Scientific evidence from various research papers supports the key properties of humus related to its texture and structure. Humus is described as having a soft, loose, and friable texture, as highlighted in the study Savich et al. (2001), which contributes to improving soil structure. The structure of humus plays a crucial role in the formation of soil aggregates, as discussed in the work by Amaya et al. (2022), creating compact structures that aid in the development of porous soil. These porous soil aggregates, as emphasized in the study by Malyk and Pankiv (2020), enhance soil permeability, allowing for the free flow of water and air, facilitating nutrient absorption, and promoting the growth of plant roots. The molecular structure of humic substances further supports this by highlighting the supramolecular associations of small molecules that contribute to the overall structure of humus, influencing soil quality and reactivity towards environmental contaminants.

The humus structure is also important for **water retention in soils**. Porous soil aggregates form micropores that can store and hold water. In this way, humus contributes to the soil's retention capacity, which is particularly important during periods of drought when plants need access to water reserves.

In addition, the humus structure can help **prevent soil erosion**. Soil aggregates formed by humus are more stable and less easily eroded by wind or water.

In summary, humus is characterised by its dark brown colour, distinctive odour, free-flowing texture and structure, all of which are essential to improve soil structure. Thanks to its properties, humus forms porous soil aggregates, increases water permeability, retains soil moisture and prevents erosion. These features contribute to better soil functioning as a substrate for plants and ecosystems.

Soil humus plays an important role **in improving soil structure** and in its ability to retain and release nutrients. This works in favour of the plants, improving their growth and health. Below, we will discuss how humus helps to improve soil structure and how it affects the sorption properties of soils.

One of the key effects of humus on soil structure is the **formation of soil aggregates**. Soil aggregates are clumped soil particles that form larger structures with a porous structure. The humus acts as a binder, bringing together fine soil particles to form larger aggregates. This type of soil aggregation improves its structure, creating permeable channels and porous spaces. This allows water, air and plant roots to move freely through the soil, increasing water permeability and soil ventilation.

Humus also affects the ability of soils to **retain and release nutrients**. Thanks to its porous structure, humus has a large specific surface area, increasing the contact surface between soil and nutrients. Organic matter in humus is able to adsorb nutrient ions, such as nitrogen, phosphorus, potassium and trace elements. In this way, humus acts as a reservoir of nutrients, accumulating them and releasing them gradually as the plants need them. This is particularly important in soils with low nutrient content, where humus can provide essential substances for plant growth.

Humus also enhances the ability of soils to **retain water**. Its porous structure allows it to store water, especially in times of drought, when this ability is crucial for plants. Humus acts like a sponge, absorbing and holding moisture, before supplying it gradually to plants. The water retained in the humus protects the soil from drying out and prevents nutrient loss through surface run-off.

In conclusion, humus improves soil structure by forming soil aggregates and increasing water permeability. In addition, its ability to retain and release nutrients increases the availability of these nutrients to plants. Humus is extremely valuable for soils and ecosystems, enhancing soil functioning as a substrate for plants, and, in turn, improving plant health and yields.

2.4.3. Regulation of soil buffering properties

Humus plays a crucial role in regulating the buffering properties of soils, particularly in maintaining optimal soil pH essential for plant growth and development. Studies have shown that humus compounds influence factors like Eh and pH, complexing ability, and structure-forming ability, all of which contribute to soil buffering (Savich et al. 2001). Additionally, humic substances act as a stable nutrient base, providing a slow-release carbon and energy source for microorganisms in the soil, further impacting soil pH regulation (Makan 2022). Furthermore, the application of humic acid has been found to enhance soil properties such as cation exchange capacity and moisture retention, which are vital for maintaining soil pH levels conducive to plant growth (Khattak et al. 2013). The quality and quantity of humus substances also influence the stability of soil aggregates, which in turn affect soil buffering properties (Tobiasová, Miskolczi 2012). Additionally, soil application of humus has been shown to significantly impact the uptake of various nutrient elements by plants, further emphasizing its role in maintaining optimal soil pH levels (Çelik et al. 2008).

Soil pH, a measure of acidity or alkalinity, has a significant impact on the availability of nutrients for plants. Plants prefer different pH ranges depending on the species, so maintaining an optimum soil pH is key to ensuring suitable plant growth conditions. This is where humus plays an important role.

The humus acts as a buffer, meaning that it is able to moderate changes in soil pH by absorbing or releasing hydrogen ions (H^+) as required. If the soil is too acidic, humus releases hydrogen ions, which helps to raise the soil pH. In contrast, in soils that are too alkaline, humus is able to absorb hydrogen ions, lowering the soil pH. In this way, humus acts as a natural pH regulator, maintaining optimum conditions for plant growth.

There are many benefits to the role that humus plays in regulating soil buffering properties. Firstly, micro-organisms that play a key role in the decomposition of organic matter and nutrient cycling function most effectively when the soil pH is well-maintained. The right soil pH provides optimum conditions for these organisms, accelerating the biological processes involved in decomposing humus and releasing nutrients.

Another benefit of humus' role in the regulation soil buffering properties is the prevention of extreme pH fluctuations. The profound acidification or alkalinisation of soils can adversely affect plant health, leading to deficits in certain micronutrients and reducing their ability to take up nutrients. Humus acts as a pH stabiliser, minimising extreme changes and ensuring balance, resulting in healthier plants and better yields.

In summary, the ability of humus to regulate soil buffering properties is essential to maintain optimal conditions for plant growth. Thanks to its buffering action, humus reduces the acidity or alkalinity of soils, providing an optimum pH. A stable soil pH favours microbial activity and biological processes and minimises extreme fluctuations, resulting in healthy plants and favourable growing conditions.

2.4.4. Effect of humus compounds on solubility and migration of metal ions

Heavy metals like lead, cadmium, copper, and arsenic are naturally present in soils due to processes like rock weathering (Mdlambuzi et al. 2023; Zwolak et al. 2019). However, anthropogenic activities significantly contribute to their excessive accumulation, posing environmental and human health risks (Rashid, Schutte 2023; Zhildikbaeva et al. 2022). We will now explain the key role that humus plays in reducing the solubility and migration of these metals in soils.

Humus compounds are able to bind and retain heavy metal ions (Rashid, Schutte 2023). During the adsorption process, humus particles form chemical complexes with metals, making them less soluble and less mobile in soils. Various chemical processes, such as complexation, ion exchange and surface adsorption, lead to the binding of humus and metals.

Humus serves a protective function, immobilizing heavy metals in soils, thereby preventing their free movement and potential migration into groundwater. The research by Muhamedyarova et al. (2020) highlights that the introduction of bio humus led to a decrease in lead and cadmium concentrations while increasing zinc and cobalt levels, indicating the ability of humus to alter metal concentrations in soils. Additionally, the study by Wu et al. (2010) demonstrates that humus soil significantly affects the chemical speciation of heavy metals like zinc and nickel in activated sludge, reducing their potential availability. Furthermore, the complex aggregate of humus includes humic substances that form stable complexes with metal ions, limiting their solubility and mobility. This evidence collectively supports the protective function of humus in binding heavy metal ions and reducing their movement within soils, ultimately safeguarding against groundwater contamination.

This process is ecologically significant; the retention of heavy metals in soils protects groundwater from contamination, helping to keep aquatic ecosystems clean and healthy. Humus acts as a natural protective barrier, limiting the spread of toxic metals and preventing their negative effects on aquatic organisms.

In addition, the ability of humus to bind heavy metals limits the availability of these metals to plants. By binding metals, humus hinders their uptake by plant roots, which can be beneficial in the case of toxic metals. Limiting the availability of heavy metals to plants reduces the risk of phytotoxicity and protects plants from the negative effects of these compounds.

Some humus fractions, especially humic and fulvic acids, form a variety of combinations with soil minerals to form salts, such as sodium and potassium humates and fulvates, or simple complex compounds and chelate complex compounds. The persistence of humic substance complexes with metals or their compounds is of great importance with regard to soil conservation (Islam 2019; Pérez-Esteban et al. 2019). The durability of these connections depends on the type of mineral component and the environmental reaction. Research by Schnitzer and Khan (1972) suggests that the persistence of these connections is greater at pH 5.0 compared to pH 3.0. Fulvic acid complexes exhibit varying persistence at low environmental pH, with a descending sequence of stability: $Fe^{3+} > Al^{\pm 3} > Cu^{2+} > Ni^{2+} > Co^{2+} > Pb^{2+} = Ca^{2+} > Zn^{2+} > Mn^{2+} > Mg^{2+}$. This ranking highlights the differential affinities of fulvic acid for various metals under acidic conditions, emphasizing the importance of pH in determining the longevity of metal-HS complexes in soil, which is essential for effective soil conservation efforts.

The mobility of metallic ions in soils and their movement into soil profiles is influenced by the nature of organic-mineral linkages, the degree of metal ion saturation, and the adsorption of the complex on soil mineral particles (Khan 2013; Jansen et al. 2004; Gillespie et al. 2021). Organic-mineral complexes play a crucial role in preventing nutrient leaching, facilitating nutrient uptake by plants, and contributing to the detoxification of toxic ions, particularly relevant to aluminium, which can be toxic, especially to root systems (Caporale, Violante 2016). This is particularly relevant to aluminium. As is well known, aluminium can be toxic, particularly to root systems. In acidic soils, root degradation is more pronounced in surface horizons rich in humus, indicating a correlation between humus content and the degree of root degradation, a trend also observed for chromium (Ondrasek, Rengel 2012). These findings underscore the importance of understanding the interactions between organic matter, minerals, and metallic ions in soil environments to manage nutrient availability, prevent leaching, and mitigate the toxicity of certain ions to plant systems.

The complexing properties of organic matter are also important in the weathering of rocks and minerals, causing them to dissolve and release elements. Fulvic acids are particularly active in weathering processes.

In summary, humus plays an important role in reducing the solubility and migration of heavy metals in soils. Its ability to bind and retain metals helps to reduce the risk of metals entering groundwater and reduces phytotoxicity to plants. In this way, humus serves an important ecological function, protecting the environment and human health from the negative effects of heavy metals.

The binding of heavy metals by humus compounds is a complex process that involves different chemical mechanisms. Humus contains a variety of functional groups, such as hydroxyl, carboxyl and phenolic groups, which are able to form complexes with metals. There are three main mechanisms that contribute to metal binding by humus: complexation, ion exchange and surface adsorption.

1. **Complexation:** Complexation consists of the formation of chemical complexes between metal ions and humus functional groups. For example, carboxyl groups in humus can form complexes with metals by connecting a metal ion to an oxygen atom from the carboxyl group. This process facilitates the formation of stable complexes that are less soluble and less mobile in soils.

2. **Ion exchange:** Ion exchange occurs when metal ions in solution replace ions of other cations bound to the caries surface. Humus is able to exchange cations, meaning that it can release bound metal ions and bind them in the humus structure. In this way, humus acts as a natural sorbent, binding metals and reducing their mobility in soils.
3. **Surface adsorption:** Surface adsorption refers to the phenomenon in which metal ions are adsorbed onto the surface of humus particles. The humus surface is characterised by high chemical activity and has many binding sites that can attract and retain metal ions. Surface adsorption helps to reduce metal solubility and migration in soils.

The binding of heavy metals by humus compounds is ecologically significant, as it leads to a reduction in the solubility and mobility of these metals in soils. Most heavy metals, are more toxic and are more to enter groundwater when dissolves. Therefore, the ability of humus to form chemical complexes and its role in ion exchange and surface adsorption are important protective mechanisms for soils and the environment.

2.4.5. Binding of pesticides by soil organic matter

Organic substances also mitigate the toxic effects of pesticides. The binding of pesticides by soil organic matter, including humus, plays a key role in protecting soils l and the environment from the negative effects of these substances. Pesticides are chemicals used to control plant pests, but their excessive presence in soils can cause damage to living organisms and contaminate surfaces and groundwater. The processes of pesticide binding by these substances take place in multiple ways, depending on the quality of each substance and the system of environmental factors, including pH and moisture content (Weed, Weber 1974). According to the authors, the sorption of cationic pesticides by humic substances consists of the exchange of cations of carboxyl (COOH) and phenolic (-OH) groups. Based on studies into the ability of humic acids to bind basic s-triazines, Sullivan and Felbeck (1968) found that the negatively charged carboxyl (-COOH) and carbonyl (C=O) groups of humic acids react with the positively charged amine groups ($-NH_3^+$) of s-triazines in this process, forming hydrogen bonds between the secondary amine and the carboxyl group. McGlamery and Slife (1966) recorded a greater increase in the sorption of atrazine by organic matter when the environment was acidic than when it was neutral. Hsu and Bartha (1976) investigated the possibility of combining humic complexes with herbicides, particularly aniline herbicides. These researchers found that the formation of the aforementioned complexes results from the reaction of the carboxyl and carbonyl groups of humic acids with the amino group of aniline herbicides. In addition, Klein and Scheunert (1982) discovered that pesticides bound by soil organic matter are only taken up by plants in small amounts. The authors present the results of studies by other authors, who proved that the plants tested (soybeans, oats, maize and wheat) in most cases took up less than 1% of pesticides bound by soil organic matter, such as butralin, trifluralin, dinitramin and prometryn.

The protection that soil organic matter provides against the harmful effects of pesticides lies not only in the chemical and physical binding of these compounds, but also in accelerating their decomposition (Alletto et al. 2010). Bioavailable organic substances also benefit from this protection, increasing the metabolic activity of soil organic matter against pesticides, as a carbon source for the microflora (Gao et al. 2010). There are several mechanisms through which humus influences the behaviour of pesticides in soils:

1. **Adsorption:** Caries has a large specific surface area and many binding sites that can adsorb pesticide molecules. Adsorption consists of the attraction and retention of pesticide particles on the humus surface. This process significantly reduces the mobility of pesticides in soils, and, in turn, the risk of such pesticides entering groundwater.

2. **Biological degradation:** Humus serves as a habitat for a variety of micro-organisms, such as bacteria and fungi, which are capable of breaking down pesticides. These microorganisms metabolise and break down pesticide molecules into less toxic or harmless compounds. These micro-organisms contribute to the natural detoxification of pesticides in soils.

3. **Chemical bonding:** Humus contains various functional groups, such as hydroxyl, carboxyl and amine groups, which can form chemical bonds with pesticides. These chemical reactions lead to the formation of stable complexes that are less toxic and less mobile in soils.

The binding of humus to pesticides is ecologically significant because it reduces the risk of groundwater contamination, and thus, the exposure of living organisms to subsequent toxic substances. By binding and detoxifying pesticides, humus helps to maintain healthy and sustainable soil quality and protect biodiversity. In addition, by counteracting the migration of pesticides, humus also helps to protect aquatic ecosystems and keep surface waters clean.

It is important to understand the role of humus as a natural detoxifying agent and its impact on the environmental pesticide cycle. Measures to conserve and increase the humus content of soils are essential to ensure the sustainable protection of soils and the environment from the negative effects of pesticide use.

2.4.6. The essence of the difference between organic matter and humus

Although they are related and both occur in soils, organic matter and humus are two separate concepts.

Organic matter encompasses a wide range of substances originating from plants, animals, and their byproducts, including living plants, dead leaves, wood, roots, fruit, and animal feces, as well as soil components like humic substances (Schinner et al. 1996; Gabriel-Ortega 2022). This organic material can exist in various forms, from fresh to highly decomposed matter, contributing significantly to soil health and plant vitality (Dharmendra

2022). The decomposition of organic matter is a vital process that provides energy for microbial growth and carbon for cell material formation, highlighting its essential role in nutrient cycling and soil quality improvement. Furthermore, the valorization of organic solid waste through techniques like solid-state fermentation demonstrates the potential for converting carbon-based waste into valuable products, emphasizing the importance of managing organic matter effectively to mitigate environmental and health risks (Reddy 2016).

In contrast, **humus** is the more advanced stage of organic matter that has undergone decomposition in soil. It is a stable form of organic matter that results from the degradation and transformation of organic matter by microorganisms and abiotic factors, such as temperature, moisture, p,H and oxygen. Humus is more stable and sustainable than raw organic matter. It is characterised by its dark brown colour and specific odour and has a well-developed structure.

A key difference between organic matter and humus is the degree of decomposition and stability (Makan 2022; Vikram et al. 2022). Organic matter is more prone to decomposition and can vary based on environmental conditions, making it less stable over time. In contrast, humus is highly durable and resistant to further decomposition, leading to its long-term presence in soils (Lanno et al. 2022). Humus, composed of humic substances, plays a crucial role in enhancing soil quality and fertility by improving water retention, soil structure, microbial activity, and nutrient uptake by plants. The stability of humus allows it to serve as a slow-release carbon and energy source for soil microorganisms, contributing to the overall health and productivity of the soil ecosystem.

Humus is crucial for soil health and ecosystem functioning. It plays an important role in improving soil structure by forming soil aggregates and increasing water permeability and nutrient retention. In addition, humus acts as a nutrient storehouse for plants, providing them with essential nutrients. It is also important in regulating soil pH and maintaining optimal conditions for plant growth.

In short, organic matter is a general term referring to organic matter in soils, while humus is a more advanced stage of decomposition of organic matter, characterised by stability and beneficial properties for soil and plants.

2.5. NATURAL DETERMINANTS OF SOIL ORGANIC MATTER CONTENT

The influence of natural factors on the organic matter content is intricate and diverse, as evidenced by various research studies. Factors such as climate, vegetation, soil type, topography, and time play crucial roles in determining the quantity and quality of soil organic matter (Siswo et al. 2023; Powlson et al. 2022; Lang et al. 2023; Balík et al. 2022). For instance, the distribution of soil organic matter fractions is influenced by soil mineralogy, plant-fungal associations, and climate conditions, showcasing the complexity of these interactions (Joy et al. 2021). Additionally, long-term experiments have shown that different management practices, such as returning crop residues or adding manures, can impact soil organic carbon levels, highlighting the multifaceted nature of soil organic matter dynamics. Understanding these complex relationships is essential for sustainable soil management practices and enhancing our knowledge of soil carbon sequestration processes.

Climate plays the key role in organic matter processes. Moist and warm climates encourage vigorous plant growth, leading to a greater presence of organic material in soils. In addition, high temperatures and humidity are conducive to the rapid decomposition of organic matter by soil microorganisms. However, extreme climatic conditions, such as prolonged drought or flooding, can reduce the organic matter content of soils by limiting plant growth and disrupting decomposition processes.

The **type of vegetation** also has a significant impact on the organic matter content of soils. The rate of organic matter production varies across different plant species, as well the amount of fallen organic material and the degree of dieback. For example, herbaceous plants are characterised by a faster death rate of organic material than woody plants, which can lead to a greater accumulation of organic matter in soil. In addition, leguminous plants, such as peas and beans, are able to absorb atmospheric nitrogen, partly determining the nature of organic matter content by supplying nitrogen to soils.

Soil type plays an important role in the variation of organic matter content. Organic soils, such as loans, peat or bog soils, naturally have a higher organic matter content because of the conditions in which they form. Meanwhile, mineral soils, meanwhile may have a lower organic matter content due to their mineral composition and the transformation processes that take place in this soil type.

The **topography of the site** also influences the organic matter content of soils. Areas with steeper slopes, such as mountain slopes, are more prone to soil erosion. Erosion can lead to a loss of organic matter, as it removes the organic-rich soil layer. In addition, topography influences soil water retention, which can also affect the rate of organic matter decomposition and organic matter accumulation.

Time is a key determinant of soil organic matter content. The process of creating organic matter is gradual and takes time. Older soils tend to accumulate more organic matter compared to younger soils. Over time, organic matter builds up in the soil, forming layers rich in organic matter.

Interlayer interactions are also important for the transport and retention of organic matter in soils. Organic matter can be transferred between different soil layers through processes such as bioturbation, percolation or capillarity. These interactions can lead to the accumulation of organic matter in specific areas of the soil, affecting soil content. Interlayer interactions play an important role in the distribution and retention of organic matter in soils. The transport and movement of organic matter between different soil layers affect the accumulation of organic matter in specific areas of soils.

Here are some examples of interlayer interactions that affect soil organic matter content:

- **Bioturbation:** Bioturbation is the process by which soil organisms, such as worms, insect larvae, annelids and plant roots, move through soils, mixing and transporting organic material. These organisms help to mix soil layers, facilitating the transport of organic matter to deeper soil layers. These organisms can also create channels that facilitate water and air infiltration, favouring soil microbial activity and the decomposition of organic matter.
- **Percolation:** Percolation refers to the movement of water through soil layers. Rainwater or irrigation water penetrates the various soil layers, taking dissolved organic matter with it. This process may facilitate the transfer of organic matter from the upper soil layers to the deepest layers, where it can be retained and stored.
- **Capillarity:** Capillarity is a phenomenon in which the water in soils rises along small cracks or pores. Water can carry dissolved organic matter up and down soils, contributing to its distribution between different soil layers. This process can also affect the migration of organic matter into deeper soil layers.
- **Root interactions:** Plant roots play an important role in the distribution of organic matter in soils. Roots can secrete organic matter that attracts soil micro-organisms, stimulating their decomposing activity. In addition, plant roots can create channels that facilitate the flow of water and organic matter between different soil layers.

Interactions between layers are extremely complex and depend on many factors, such as soil structure, chemical composition, biological activity and physical processes. All these interactions affect the distribution of organic matter in soils and determine its content in the different layers. Understanding these processes is key, not only to protect and manage soils more effectively, but also to maintain their ability to provide plant nutrients and regulate many ecosystem services.

2.6. RATIONAL MANAGEMENT OF SOIL ORGANIC MATTER

The rational management of soil organic matter through practices like the use of organic fertilisers, composting, and reduced tillage not only enhances agricultural yields but also positively impacts the environment. Studies have shown that organic management leads to higher nitrogen use efficiency, improved soil quality, and increased soil organic carbon content, promoting sustainable agriculture (Toda et al. 2023). Additionally, reduced tillage practices combined with organic inputs have been found to increase soil stability, organic carbon content, and promote the formation of soil aggregates, contributing to enhanced soil health and sustainability (Panagea et al. 2022). Furthermore, integrated soil-crop management systems have demonstrated increased crop yields, higher soil organic carbon content, and a shift towards beneficial bacterial communities, highlighting the importance of managing soil organic matter for both productivity and environmental health (Li, Kumar 2023). Overall, maintaining soil organic matter through appropriate management practices is crucial for sustainable production systems, soil quality improvement, biodiversity conservation, and mitigating negative impacts on soil ecosystems (Das et al. 2022).

Below are some key points on the rational management of organic matter:

Rational management of organic matter contributes to soil sustainability. Through appropriate practices, such as the application of organic fertilisers, composting and the use of cover crops, it is possible to maintain a balance in soil chemistry and provide organic matter, which plays an important role in soil fertility.

Composting is an effective technique for converting organic waste into valuable organic fertiliser. This process consists of the decomposition of organic matter by micro-organisms in the presence of oxygen. Applying compost enriches the soil with organic matter, increases its water retention capacity, improves soil structure and stimulates micro-organism activity.

Ground cover crops, such as clover, phacelia or vetch, are used to cover the soil between crops. They are able to grow and die quickly, providing a large amount of organic matter to soils. Ground cover crops prevent soil erosion, retain moisture and improve soil structure.

Avoiding overgrazing: Overgrazing by animals can lead to the removal of vegetation from soils, resulting in a loss of organic matter. In order to manage organic matter rationally, it is important to avoid overgrazing and to maintain adequate vegetation that dies back and provides organic matter to soils.

No-till practices: No-till practices, or cultivation using technologies that reduce ploughing, preserve organic matter in soils. Ploughless cultivation methods minimise disruption to the soil structure and reduce the loss of organic matter, contributing to the long-term maintenance of soil fertility.

Use of sustainable organic fertilisers: Sustainable organic fertilisers, such as manure, compost, slurry or other fertilisers of organic origin, are a valuable source of organic matter and nutrients for soils. The use of these fertilisers provides organic matter, improves soil structure, increases water retention and provides plants with essential nutrients.

Monitoring and evaluation: Systematic monitoring and assessment of soil organic matter content are essential to track progress in organic matter management. Regular soil surveys make it possible to determine the current state of organic matter, identify areas for improvement and adapt organic matter management practices to the specific needs of soils.

2.7. RELATIONSHIP BETWEEN HUMUS AND THE HEALTH OF LIVING ORGANISMS, INCLUDING HUMAN HEALTH

As a rich source of soil organic matter, humus plays an important role in the health of living organisms, including that of humans. There are several important health-related aspects that link caries to benefits for living organisms:

Source of nutrients: Soil humus is a natural storehouse of nutrients, such as macro- and micronutrients, which are essential for the proper functioning of living organisms. Plants that derive their nutrients from soil become enriched in these substances, which are then passed up the food chain. When people eat fruit, vegetables, cereals and other plant-based foods, they benefit from these nutrients, which is key to maintaining good health and proper bodily function.

Healthy gut flora: The humus found in soils is rich in micro-organisms, such as bacteria and fungi, which play an important role in human health. Bacteria of the genus Bacillus, Pseudomonas or Streptomyces, present in humus, are friendly to living organisms and can influence health by producing beneficial substances such as probiotics. These beneficial bacteria influence the balance of human intestinal microflora, which is crucial for proper digestion, nutrient absorption and strengthening the immune system.

Water retention: The humus found in soils is able to retain water, which is important for the health of living organisms, including that of humans. The ability of soils to retain water affects the availability of water to plants and, as a result, their healthy growth and crop production. In addition, as a consumer, adequate hydration of plant foods, which draw nutrients from soils, affects their quality and nutritional value.

Reduction of soil erosion: Humus also plays an important role in maintaining soil structure and reducing erosion. A strong soil structure, supported by the presence of organic matter, will protect soil from erosion caused by wind and water. Humus acts as a natural glue, creating soil aggregates that are more resistant to erosion. Reducing soil erosion is crucial to maintaining soil fertility and the ability to support healthy plant growth and food production.

All these aspects link humus to health benefits for living organisms, including humans. Managing soils in a way that favours humus development, such as sustainable cultivation practices, using organic fertilisers and avoiding excessive pesticide use, is key to maintaining the health of soil ecosystems and producing high-quality and nutritious food.

Soil humus not only plays an important role in the provision of nutrients and the healthy functioning of living organisms, but also contributes to many other health benefits. Here are some additional aspects to consider:

Environmental detoxification: humus is able to detoxify the environment by binding and degrading harmful chemicals, including pesticides and industrial pollutants. Micro-organisms present in humus can decompose these substances, reducing their toxicity and potential negative effects on living organisms. In this way, humus acts as a natural filter, protecting both the soil and groundwater from contamination.

Soil pH regulation: Humus plays an important role in regulating soil pH. Its presence influences the maintenance of an optimum pH, which is important for the availability of nutrients for plants. Soil pH that is too acidic or too alkaline can limit the ability of plants to take up nutrients, which negatively affects their growth and health. Humus acts as a buffer, reducing extreme changes in pH and keeping soils within the optimum range.

Increasing the bioavailability of nutrients: Humus enriches soils with organic matter, which serves as a source of nutrients for plants. However, it is not only the amount of nutrients in soils that is important, but also their bioavailability. Humus improves soil structure by forming aggregates, which, in turn, increases the soil's ability to retain nutrients and prevent leaching. This gives the plants better access to nutrients, resulting in healthy growth and development.

The cultivation of beneficial microflora, including bacteria, fungi, and protozoa, is crucial for enhancing soil health and promoting plant growth, as supported by various research papers (Kumar, Singh 2021; Kaur, Rani 2022). These beneficial soil microorganisms play a vital role in biological processes within the soil, such as organic matter decomposition, the nitrogen cycle, and nutrient uptake by plants. Effective management of organic matter and the stimulation of humus development are essential for fostering a favorable soil microbiome, which in turn positively impacts soil and ecosystem health. By promoting the growth and activity of beneficial soil microorganisms through humus stimulation, agricultural practices can improve soil fertility, enhance plant productivity, and contribute to sustainable agricultural systems.

The rational management of soil organic matter is therefore crucial to maintain healthy and fertile soil ecosystems and to provide healthy and nutritious food for humans. Appropriate agricultural practices, such as composting, the use of cover crops and sustainable organic fertilisers, are key to protecting and maintaining humus in soils, contributing to sustainability and long-term environmental health.

CHARACTERISTIC OF BROWN COAL (LIGNITE)

Brown coal, or lignite, holds significant importance as a fossil fuel, with its characterization encompassing various facets like chemical composition, structure, genesis, and resources (Zhao, Baker 2023). Lignite is classified as a low-rank coal and is often treated chemically or enzymatically before utilization for energy and materials (Bone 1921). The global coal reserves consist of a substantial portion of sub-bituminous and lignitic coals, highlighting their economic relevance, especially in light of challenges faced by higher-ranked coals (Zawada 2018). Research indicates that lignite mining industries, such as in Poland, play a strategic role in providing stable, environmentally friendly, and cost-effective electricity, emphasizing the necessity of retaining lignite potential beyond 2030 (Maciejewska et al. 2022). In this chapter, we will conduct a thorough analysis of the characteristics of brown coal in order to better understand its properties and importance in various fields, particularly in terms of environmental protection and agriculture, as a natural soil conditioner.

The first aspect that we will cover is the chemical composition of brown coal/lignite. This natural resource consists mainly of carbon, hydrogen, oxygen, nitrogen and sulphur. This composition can vary depending on the specific deposit, which affects its energy, fertiliser and other properties. Knowing the chemical composition of brown coal is key to determining its potential for use in various sectors.

Another important aspect is the structure of brown coal. Brown coal has a lower degree of carbonisation compared to other types of coal, such as hard coal or anthracite. The structure of lignite influences its strength, brittleness and ability to be processed and used in various processes. This is explained by its younger geological age and shorter formation period compared to hard coal.

The genesis of lignite is another key aspect of its characterisation. Lignite is formed by the long process of peat formation, which is later transformed into lignite. Studying the genesis of lignite allows us to understand what geological and environmental factors contributed to their formation. Learning about the genesis process is important from both a scientific and practical perspective, as it allows for a better assessment of their resources and mining potential.

An important aspect of the characterisation of lignite is its distribution and reserves worldwide, including in Poland. Lignite is found on different continents and in different regions, with varying quantities and availability. By analysing the distribution and resources of lignite, it is possible to assess its potential as a raw material for energy and as a fertiliser, as well as its impact on the country's economy.

In summary, the characterisation of lignite includes chemical composition, structure, genesis, and distribution and resources. Understanding these aspects is key to assessing the potential of lignite and its various uses. In the following subsections of this chapter, we will explore these topics in greater depth in order to better understand and appreciate lignite as an important natural resource that can be used, among other things, to heal soils, particularly those used for agriculture, as well as chemically degraded soils.

3.1. TYPES OF LIGNITE

Lignite is one of the main types of coal, along with hard coal and anthracite. As a significant type of coal it is characterized by its degree of carbonization, chemical composition, and energy properties, impacting its applications and performance (Bao et al. 2013; Purba et al. 2020). Lignite deposits' genesis is intricately linked to specific geological conditions influenced by local factors like geology, climate, relief, and palaeogeographical history, which collectively determine the quality, chemical composition, and abundance of these deposits (Mitrovic et al. 2016). The chemical structure of lignite, as revealed by solid-state NMR techniques, showcases differences in carbon skeletal structures between lignite types, impacting their properties and applications (Mitra et al. 1987). Additionally, the calorific value and grindability properties of lignite vary based on its composition, with xylite-rich coal exhibiting distinct characteristics and suitability for specific processes like fluidized bed gasification. These findings underscore the importance of understanding the geological and chemical intricacies of lignite for optimizing its utilization and performance in various applications.

Geological processes and the transformation of organic matter over tens of millions of years result in lignite deposits of varying quality and use value. These deposits are an important natural resource that is used in various economic sectors, including energy, chemicals and agriculture.

Lignite occurs in various forms as a result of the carbonisation of plant material and can be divided into three main types: brown coal, sub-bituminous lignite and bituminous lignite. These types of lignite mostly differ in their carbon content as an element and the degree of carbonisation, which affects their physical and chemical properties, particularly their energy properties.

Brown coal: The most common type of lignite. It has a relatively low carbon content, usually less than 70%. It also has a low degree of carbonisation and high moisture content, making it less combustible compared to other coals. Lignite, also known as brown coal, is often used as an energy resource to generate electricity and produce heat.

Sub-bituminous lignite: This type of lignite has a higher carbon content (70-80%) and a higher degree of carbonisation than brown lignite. It also has a lower moisture content, which translates into better combustion properties. Sub-bituminous lignite is often used as a raw material in the chemical and energy industries.

Bituminous lignite: It is the most advanced carbonised type of lignite. It has a high carbon content (above 80%) and lower moisture content. Bituminous lignite has the best combustion properties of all types of lignite. It is used primarily in the chemical industry, power generation and as a raw material for coke production.

It is worth noting that the differences in chemical composition and combustible properties between different types of lignite are mainly explained by their genesis and geological history. The processes of sedimentation, diagenesis and microbial activity are central to the formation and characterisation of lignite.

Based on the provided research papers, different varieties of lignite are distinguished by their physical and chemical properties. ***Xylitic* coals** (from Greek *xylon* - wood), also known as lignite, exhibit a well-preserved wood structure (Sprunk 1942). **Soft coals**, such as shale and earthy coals, have a consistency resembling soil or old peat (Miller 1977). On the other hand, **hard coals**, like matt glossy coals, are characterized by high elemental carbon content and mechanical strength, akin to stone coals (Oh et al. 2012). These distinctions in properties are crucial when considering the classification and utilization of lignite varieties, highlighting the diverse nature of coal formations and their potential applications in various industrial processes.

3.2. GENESIS OF LIGNITE DEPOSITS

The genesis of lignite deposits, a type of coal, is intricately linked to geological processes that have been ongoing for hundreds of millions of years, particularly during the Carboniferous and Permian periods (Kouzin 2018). Lignite formation primarily involves the accumulation of woody plant debris in peat swamps or marshes, as evidenced by palaeobotanic studies (Maltsev et al. 2018). Additionally, the time factor plays a crucial role in the formation and development of giant ore deposits, with different geological periods influencing the concentration of elements in these deposits (Gruszczyk 1982). Furthermore, the study of man-made mineral deposits emphasizes the importance of efficient mining operations, environmental impact reduction, and land restoration, showcasing the multifaceted nature of resource creation through geological processes (Given 1988). These findings collectively support the notion that lignite deposits are the result of complex geological processes that have shaped natural resources over extensive periods of time.

Lignite deposits are mainly formed by organic sedimentation, the accumulation of dead plant matter under specific conditions. This process usually takes place in marshes, lakes and wetlands, where hydrological conditions favour the accumulation of large amounts of organic matter. The vegetation layers gradually compress under pressure and settle to the bottom of the water body.

An important factor influencing the genesis of lignite deposits is the presence of water, which acts as a thermal insulator, keeping temperatures low and preventing full degradation of organic matter. Furthermore, oxidation conditions are restricted within the aquatic reservoir, favouring the preservation of a larger quantity of organic matter.

Time and pressure are crucial for the further conversion of organic matter into lignite. Under the influence of geological processes, such as subsidence, thermogenesis and diagenesis, the plant layers gradually transform into an increasingly carbon-like form.

It is worth noting that the genesis of lignite deposits is linked to the specific geological conditions of a region. Local factors, such as geology, climate, relief and palaeogeographical history, influence the quality, chemical composition and productivity of lignite deposits.

According to the literature, lignite was formed by the transformation of plant material at the end of the Cretaceous period. It is classified as sedimentary rock of organic origin.

Sedimentary rocks of organic origin, known as bioliths, play a crucial role in various geological processes and resource exploration (Nims et al. 2021). Within this classification, two distinct groups of joints are identified: caustobiolites and acaustobiolites. Caustobiolites represent sedimentary rocks that are combustible, deriving their name from the Greek words kaustos (combustible), bios (living), and lithos (stone) (Arif 2021). On the other hand, acaustobiolites consist of non-combustible rocks of organic origin (Jiang et al. 2016). These organic-rich rocks are significant as they can serve as sources of gas, oil, and even precious metals like copper, gold, and silver (Gilbert et al. 2005). Understanding the composition and characteristics of these bioliths is essential for various applications, ranging from resource extraction to environmental microbial community studies.

Bioliths, as rocks of organic origin, share a common feature with living matter, as they are composed of the same elements, i.e. carbon, hydrogen, oxygen, nitrogen, sulphur, and phosphorus (Tengler 1981). The division of bioliths in schematic terms is shown in Figure 17 (Hubacek et al. 1962).

Carbon, as evidenced by various studies (Rankama 1948; Krzesińska et al. 2006; Reyerson et al. 2015), undergoes a process of transformation known as coalification or carbonisation, leading to the formation of caustobiolite, an organic rock enriched in carbon (C) derived from plant material. This transformation initiates during the biochemical phase, encompassing peat formation and decay, and progresses through the geochemical phase involving diagenesis (lignite formation) and metamorphosis (coal and anthracite formation). The biochemical phase significantly influences the resulting carbon nature, with lignite positioned between peat and hard coal in the coalification series of primary plant material. The studies highlight the complex processes involved in the conversion of plant material into carbonaceous rocks, shedding light on the stages and factors shaping the final composition and properties of carbon-rich materials.

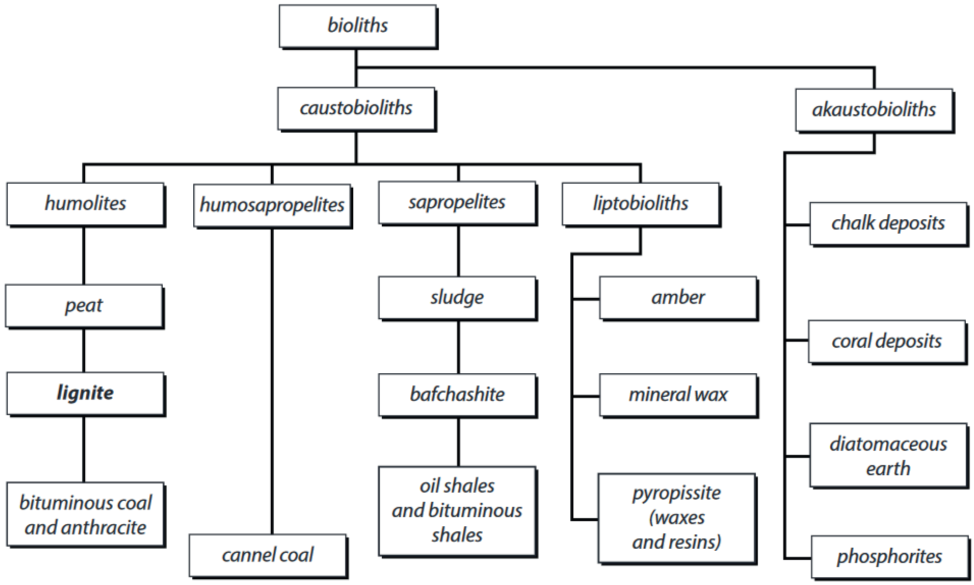

Figure 17. Division of rocks of organic origin.

Source: own elaboration based on Kalembasa and Tengler (1992).

The formation of coal deposits is a very complex process that depends on many conditions, such as the development of flora and microorganisms, climate, morphology and tectonics of the area (Roga 1958).

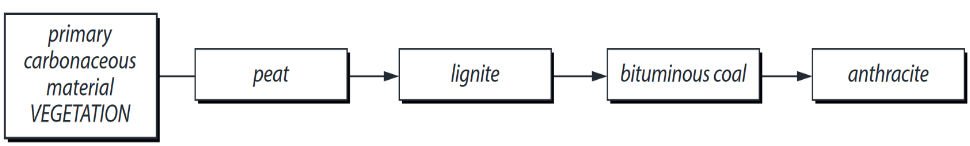

Figure 18. Diagram of the carbonisation process.

Source: based on Maciejewska (1998).

An important factor in the formation of coal deposits is the relief of the land. Most brown coal deposits formed in sinkholes, the areas of the Earth's crust that underwent subsidence, referred to as geosynclines (Behera et al. 2020). The speed of geosyncline descent influenced sedimentation rates, with slower declines leading to increased sedimentation and the development of shallow lagoons conducive to aquatic plant growth and peat bog formation (Gao et al. 2023). In sedimentary basins, smaller coal deposits with fewer seams, predominantly lignite, were created in depressions on onshore platforms like the Lower Carboniferous sub-Moscow and Tertiary Central European deposits (Zaitseva, Ivanova 2020). These processes highlight the significance of land subsidence and sedimentation in the formation of coal deposits, particularly brown coal, in various geological settings.

In periods prior to the development of terrestrial flora, the starting material in the carbonisation process was probably aquatic vegetation, primarily algae. It is believed that the oldest Precambrian coal, shugite, was formed from such vegetation, which has a similar degree of carbonisation to graphite.

The evolution of terrestrial plants, from psilophytes in the Devonian to diverse vegetation in the Carboniferous to Tertiary periods, played a crucial role in the formation of coal deposits (Collinson et al. 1994). The earliest plant remains in the Rhenish Shale Mountains contributed to the formation of shiny humic coals, with subsequent rich vegetation providing source material for coal deposits over geological time (Kennedy et al. 2013). Different plant components exhibit varying susceptibility to decomposition, with lignin, cellulose, leaf epithelia, spores, pollen, resins, waxes, and fats being the most resistant and decomposing only at high temperatures, characteristic of the coal stage (Boyce et al. 2003). Plasma and sugars are the most easily broken down. This highlights the complex composition of plant materials contributing to coal formation and the differential decomposition rates of various components based on their chemical nature and environmental conditions.

According to Potonié, a German botanist and paleobotanist known for his research on coal formation, there are four stages in the processes of decomposition and transformation of plant parts: humification, putrefaction, peatization, and decay (Potonié, Gothan 1921), as shown in Table 8. The decomposition of plant material in the peat process is determined by the presence of water and access to oxygen from the air. The catalytic effect of the minerals also has a small effect.

Table 8. Diagram of processes and products of decomposition of plant material.

<table>
<tr><th rowspan="2">type material</th><th rowspan="2">process distribution</th><th colspan="2">access</th><th colspan="2">chemical reactions</th><th colspan="2">final product</th></tr>
<tr><th>oxygen</th><th>waters</th><th colspan="2">full oxidation</th><th colspan="2">no combustible products possibly liptobiolites</th></tr>
<tr><td rowspan="3">terrestrial vegetation and swampy</td><td>rotting</td><td>full</td><td rowspan="2">presence of dampness</td><td rowspan="4">mainly reduction</td><td rowspan="3">coalification</td><td rowspan="3">hydrocarbons rich in element C</td><td>humus</td></tr>
<tr><td>decompo-sition</td><td>this</td><td rowspan="2">peat</td></tr>
<tr><td>peating</td><td>partial absence</td><td>dampness, then stagnant water</td></tr>
<tr><td>aquatic vegetation</td><td>decay</td><td>without access</td><td>stagnant waters</td><td>bitumination</td><td>hydrocarbons rich in the element H</td><td>sapropel</td></tr>
</table>

Source: own elaboration based on Kalembasa and Tengler (1992).

Plant material decomposition in peatlands is a complex process influenced by various organic factors, as supported by research (Boonman et al. 2023). Enzymes, fungi, aerobic, and anaerobic bacteria play crucial roles in breaking down water-saturated lignin-cellulosic material, initiating humification, and converting it into humic acids (Philben et al. 2014). The decomposition rate varies with factors like soil moisture, plant types, and microbial communities, affecting the extent of peat decomposition (Tfaily et al. 2014). Studies have shown that the extent of peat decomposition is linked to oxygen exposure time, with longer exposure leading to more decomposition, highlighting the importance of aerobic and anaerobic conditions in the process. Additionally, molecular-level analyses have revealed the quality of organic matter in peatlands, indicating shifts in vegetation types can impact carbon gas emissions and decomposition mechanisms. This humification process marks the beginning of the peat stage, progressing into soft brown coals through diagenesis, showcasing the intricate biochemical transformations occurring in peatlands.

Humification of organic matter in peatlands involves the formation and development of aromatic structures through a series of reactions catalyzed by microorganisms, as supported by (Hatcher et al. 2019). The decomposition process is most intense in the surface layer due to aerobic bacteria, while deeper layers exhibit less intense decomposition with anaerobic bacteria activity (Field, Cervantes 2005). Both oxidation and reduction reactions occur during humification, leading to an increase in elemental C content and a shift from biochemical to chemical decomposition (Tfaily et al. 2014). As humic acid content rises, peat becomes more acidified (Mastný et al. 2018). Additionally, humic substances rich in quinone moieties play a crucial role in anaerobic transformations, acting as electron acceptors and redox mediators. This comprehensive understanding highlights the intricate microbial and chemical processes driving humification in peatlands.

Decay, alongside peatisation, is the second parallel direction of **biochemical phase** transformation. This process takes place in an aquatic environment in which the organic world consists of algae, plankton, the remains of higher plants, and the remains of animal organisms. This material deposited at the bottom of the reservoir decayed under the action of anaerobic bacteria, becoming enriched in the elements C and H. The product of putrefaction is septic slime (sapropel), the starting material for sapropel formations.

The biochemical phase of humic carbon ends when there is no longer over-acidification of the environment and aseptic conditions, which are lethal to bacteria, are produced. The completion of the biochemical phase usually coincides with the formation of an overburden layer above the peat. The peat process progresses to diagenesis, the stage of lignite formation (Hamberger 1981).

The transition of peat to lignite involves a progression from the biochemical phase to the geochemical phase, characterized by diagenesis and metamorphosis stages, leading to a decrease in free energy reserves (Melenevskii et al. 2019). In the geochemical phase, intense chemical reactions occur, including the formation of humic acid anhydrides and the condensation of humic acids with other compounds, alongside the release of gaseous products like CO_2, NH_3, H_2S, and CH_4 from coal seams (Jommi et al. 2017; Duan et al. 2011). These processes involve the interaction of functional groups and are influenced by increased temperatures, which accelerate the transformations and introduce new reactions not present in earlier stages of coalification (Willis et al. 1991). Additionally, laboratory simulations demonstrate the reorganization of organic compounds and extensive petrographic changes during the diagenesis of peat, highlighting the complexity of the chemical processes involved in the transition to lignite (Ting 1977).

Research provides insights into the impact of physico-chemical factors on plant mass during diagenesis, particularly the temperature and its duration, pressure, the influence of gases and mineral substances. Under the influence of temperature, the transformation of humic acids into their salts, humates, takes place during diagenesis. In the early stages of diagenesis, the humate content of the lignite is 60-80%, but this decreases in favour of their salts as coalification progresses. Studies have shown that diagenetic changes affect the molecular compositions of plant materials, with variations in concentrations of fatty acids, alcohols, and hydrocarbons observed over time (Meyers et al. 1995). Additionally, the decomposition of plant material in acidic mining sediments highlights the role of sediment conditions, microbial activity, and plant invasion in organic matter degradation (Chabbi, Rumpel 2004). Furthermore, investigations into coal waste materials reveal the inhibitory effects on vegetation establishment due to adverse physical and chemical properties, emphasizing the importance of topsoil treatments for successful surface revegetation (Li et al. 1998). Moreover, analyses of plant biochemicals in anaerobic environments demonstrate extensive decay and the formation of geochemical compounds over time, indicating the transformation of organic remains into microbial products during decomposition (Fogel, Tuross 1999). These findings collectively support the notion that physico-chemical factors play a crucial role in the diagenetic processes affecting plant mass and organic matter transformations.

The main factor in structural change is pressure. Under its influence, the pores are compressed and the hydroxyl groups separate, resulting in a reduction in water content from 60% in soft brown coal to 30% in hard coal and 10% in glossy coal (Hamberger 1981).

During the process of diagenesis, that is, the stage where lignite formation takes place, the soluble humic acids are transformed into the insoluble salts (humates) inherent in hard coal.

3.3. LIGNITE RESOURCES AND THEIR DISTRIBUTION

Lignite is one of the important energy resources on the planet, with reserves linked to the geological and paleoclimatic conditions of the past. The distribution of lignite resources worldwide, including in Poland, reflects geological and paleogeographical processes from hundreds of millions of years ago (Thielemann 2012; Macgregor 1994; Wang et al. 2016). Poland, rich in lignite, possesses substantial reserves estimated at 23.5 billion Mg, ensuring long-term energy security for the country (Naworyta 2016). The lignite districts in Germany and the Czech Republic also highlight the importance of lignite as a primary energy source historically, with large reserves available for extraction (Schultze, Geller 1996). Understanding the geological and paleoclimatic factors that influenced the formation and distribution of lignite resources is crucial for sustainable exploitation and utilization of this valuable energy source.

3.3.1. Global lignite resources

Lignite reserves are abundant globally, with significant deposits found in countries like Germany, Russia, the United States, China, India, Australia, and Canada. These reserves are closely tied to geological processes involving peatland formation and organic matter deposition (Blaizot 2017). Germany, for instance, has substantial lignite reserves, comprising 10% of the world's total and 50% of Europe's reserves (James 1984). Additionally, lignite has been a major energy source historically, with 90% of power generation in the former German Democratic Republic based on brown coal (Jubert, Masudi 1995). The distribution of lignite reserves is influenced by specific geological settings, with coal sequences in certain regions being primary oil-prone source facies, contributing significantly to gas reserves (Schultze, Geller 1996). This highlights the geological significance and distribution patterns of lignite reserves worldwide.

Lignite is particularly common in areas with humid climates, where favourable conditions allow organic matter to accumulate and transform into peat. Lignite deposits are often found close to the ground surface, which makes them easier to exploit.

It is worth noting that global lignite resources are limited and their extraction poses various environmental and economic challenges. Consequently, in recent years, research and technological solutions have been aimed at developing more efficient and sustainable extraction methods and searching for alternative energy sources.

3.3.2. Lignite resources in Poland

Poland possesses substantial lignite resources, crucial for its energy security and economy. The country's lignite deposits, primarily situated in Silesia, Greater Poland, and the Lublin region, are ensuring long-term mining and energy production potential (Naworyta 2016; Maciejewska et al. 2022). Lignite plays a vital role in Poland's energy sector, with the power industry heavily reliant on coal and lignite for stability and independence (Przybyłka, Manko 2016; Maciejewska et al. 2022). Economic competitiveness further highlights lignite's significance, as it offers cost advantages in electricity production compared to other fuels (Krawczykowska, Marciniak-Kowalska 2012; Maciejewska et al. 2022). The complex geology of these lignite-bearing areas, influenced by tectonic and glaciotectonic processes, underscores the need for careful exploration and exploitation planning to maximize resource utilization (Widera 2018). Additionally, Poland's high level of energy self-sufficiency, driven by its abundant hard coal and lignite resources, emphasizes the strategic importance of the mining sector in ensuring the country's energy security and economic stability (Bluszcz et al. 2022).

Poland's lignite resources are extensive and their distribution is related to geological and palaeogeographical differences between regions. The formation of these resources is linked to the accumulation of peat during the Cenozoic period and the subsequent transformation of this peat into lignite.

Research in Poland highlights the significant role of lignite extraction in meeting energy and industrial needs, including the chemical industry and agriculture (Dmochowska-Dudek, Wójcik 2022; Wrzaszcz, Prandecki 2015; Maciejewska et al. 2022). However, the economic development approach must consider environmental sustainability, leading to investigations into technologies for more efficient and environmentally friendly lignite extraction (Maciejewska et al. 2022; Bluszcz et al. 2023). Poland's rich lignite resources are crucial for the country's energy security, emphasizing the importance of responsible resource management and extraction methods (Naworyta 2016). The lignite mining industry in Poland faces challenges in terms of future development limitations, requiring a balance between economic growth and environmental protection (Zawada 2019). This underscores the necessity of advancing technologies to ensure sustainable lignite extraction practices align with environmental and economic considerations.

The distribution and use of lignite resources requires close cooperation between the scientific sector, public administration, industry and the local community. These measures aim to minimise the negative environmental impact of lignite mining, improve the efficiency of extraction and seek alternative and more sustainable sources of energy.

Poland is a significant player in lignite exploitation, ranking among the top lignite-producing countries globally in terms of both recognized reserves and annual output (Naworyta 2016). The lignite deposits in Poland are primarily associated with Tertiary formations, particularly from the Miocene period, forming part of the vast basin of the European Lowlands extending from the Vistula to the Rhine, with concentrations in central and north-western Poland (Widera 2016). These deposits are well-recognized geologically, with estimates indicating substantial resources available for extraction, contributing significantly to the country's energy security and economy (Kasiński et al. 2008). The utilization of alternative methods like underground gasification is also being explored to mitigate the environmental and social conflicts associated with traditional open-cast mining practices. Between 1979 and 1985, the Polish Geological Institute developed and implemented the *Comprehensive Programme for the Exploration of Lignite Deposits*, commissioned by the former Central Geology Office. Modern geological reconnaissance methods were applied and more than 80% of the country's area containing Tertiary sediments with potential coal-bearing capacity was explored. As a result of this work, lignite resources were documented as follows, according to PIG's mineral resources balance: there are 159 deposits with proven reserves and 43 occurrences of lignite with defined parameters and undefined reserves. Within the group of 159 lignite deposits, the following distinctions are made:

- **13 deposits** developed **or** in preparation for development, with category B, C1 and C2 tested balance resources of 3.3 billion tonnes,
- **46** undeveloped **deposits**, with an assayed balance sheet resource of **14.4 billion tonnes** in Categories B, C1 and C2,
- **5 deposits** with off-balance-sheet resources recognised in category C2, amounting to 0.1 billion tonnes,
- **71 deposits** with prospective resources (estimated balance sheet) initially recognised in category D, amounting to 10.3 **billion tonnes**,
- **12 deposits** with potential resources (off-balance sheet estimates) classified as category E, amounting to 8.1 billion tonnes,
- **12 deposits** recognised in Categories B, C1 and C2, with discontinued and remaining resources of 0.7 billion tonnes, have been identified.

Total lignite reserves amount to 36.9 billion t (Bielikowski 1995).

However, it should be emphasised that the assessment of deposits was carried out in accordance with the criteria set out in 1978 by the former Minister of Energy and Atomic Energy, where technical and quality parameters were adopted according to the state of mining and combustion technology in the power boilers of the time. There is now a need to update these criteria given recent advancements in these fields, particularly in combustion technology, resulting in an increase in balance reserves. Coals and deposits previously considered off-balance are now industrially utilised and can be included. It may therefore be argued that domestic resources of lignite deposits, according to the new criteria, may, after further detailed appraisal, amount to approximately 70 billion tonnes. In addition, there are also known and recognised small deposits of several to tens of million tonnes of resources, of which there are more than 350 in Poland. Some of these resources lie no more than 20 m below the surface. These deposits can also be used locally as a raw material for fertilising soils, especially light and chemically degraded soils.

The most significant documented lignite deposits for potential industrial use are found in the following 14 provinces:

- **Bydgoskie:** 2 deposits (Chelmce and Szubin) with total resources of 44.3 million t;
- **Gorzów:** 2 deposits (Sieniawa VIII and Sieniawa IX-XVI) with total resources of 106.2 million tonnes. A large deposit was found in the Rzepin-Torzym area during the course of geological research, as well as several others in the Sulęcin, Giżyca and Ośno areas. Initial reserves of these deposits are estimated at more than 1.5 billion t;
- **Jeleniogórskie:** 4 deposits (Turów, Kalawsk, Radomierzyce, Forgotten) with total reserves of 798 million t;
- **Konin:** 22 deposits with total resources of 606.7 million t (either in operation or as reserves for active mines);
- **Legnicki:** 6 deposits (Legnica North, Legnica East, Legnica West, Lusina Udanin N, Lusina S and Ścinawa) with total resources of 3813.8 million t;
- **Leszczyńskie:** 2 deposits (Gostyn and Krzywin) with total resources of 2655.3 million t;
- **Lódź: 1 deposit** (Rogórzno) with resources of 551.2 million t;
- **Pilskie:** 1 deposit (Trzcianka) with resources of 300.0 million t;
- **Piotrkowskie:** 3 deposits (Bełchatów, Szczerców and Kamieńsk) with total resources of 1773 million t. Recent geological surveys indicate the presence of a deposit south-east of Bełchatów (Gorzkowice-Reczno) with resources of at least 150 million t;
- **Poznań:** 1 deposit (Czempin) with resources of 1034.5 million t;
- **Radomskie:** 3 deposits (Głowaczów, Owadów and Wola Owadowska) with reserves of 92.6 million t;
- **Sieradzkie:** 1 deposit (Złoczew) with resources of 485.6 million t;
- **Włocławek:** 3 deposits (Brzezie, Kobielice and Lubraniec) with total resources of 60.5 million t;
- **Zielonogórskie:** 16 deposits (6 deposits named Babina, 6 deposits named Sieniawa, Cybinka, Gubin, Mosty, Sądów and Przyjaźń Narodów) with total resources of 1086.6 million t;

Polish lignites belong to the xylitic-earth coals and, assessed according to energy criteria, have the following basic parameters (Table 9.).

Table 9. Quality of Polish brown coal.

Parameters	Min	Max	On average
Calorific value [MJ/kg]	5.6	11.7	9.5
Ash content [%]	4.0	40.0	16.0
Sulphur content [%]	0.2	1.7	0.7
Bitumen content [%]	4.0	11.0	6.0

Source: based on Maciejewska (1998).

These are mainly thermal coals; however, a significant proportion, up to 40% in individual deposits, is suitable for briquetting, while about 15% is suitable for chemical processing. A large proportion, especially of waste earth coals, can be successfully used in agriculture to enrich soils with organic matter.

3.4. CHEMICAL COMPOSITION OF LIGNITE

The chemical composition of lignite includes both mineral composition and organic composition, which have a significant impact on their properties and use. This composition can vary considerably depending on their origin, genesis and degree of organic metabolism.

The mineral composition of lignite is intricately linked to the geological setting of lignite deposits, encompassing various minerals like clay minerals, sands, and shales (Miller 1978). These minerals significantly impact both the physical and chemical properties of lignite. The inorganic matter associated with lignites can exist as discrete mineral phases or be cations linked with organic matter, influencing the role and fate of inorganic matter in processes utilizing lignites (Ting et al. 1973). Additionally, the elemental composition of lignite ash residues affects temperatures related to ash fusibility, slagging onset, and liquid slag removal, with melting temperatures influenced by oxides like SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO (Filho et al. 2018). Furthermore, the ash content in lignite affects the chemical composition of the ash, with high contents of Fe_2O_3, CaO, and MgO impairing coke quality indicators like CSR and CRI (Fedorova, Ismagilov 2019).

The organic composition of brown coals is intricately linked to the presence of diverse chemical compounds and elements found in deceased plant matter. Studies have revealed that brown coals contain organic functional groups like carbon, hydrogen, oxygen, nitrogen, and sulfur, with lignite potentially harboring trace amounts of elements such as potassium, phosphorus, magnesium, and copper (Domazetis et al. 2006). The chemical structure of lignin, a stable biopolymer in plant material, plays a crucial role in coal formation, with lignins categorized into different types based on their composition (Kocheva et al. 2019). Additionally, the petrographic analysis of brown coals highlights variations in their elemental content, with factors like ash content, volatile substance yield, and vitrinite index influencing their energy properties and potential applications in various industries (Fedorova et al. 2019). Moreover, the application of brown coal in soil has been shown to impact the properties of humic acids, enriching them in carbon and affecting their thermal stability (Kwiatkowska-Malina et al. 2005).

Analyzing the chemical composition of lignite is crucial as it allows for the study of humic acid content, a vital component of humic substances with high molecular weight (Jia et al. 2020). Chemical modifications, such as alkylation and oxidation, can alter the functional group composition of humic acids derived from lignite, affecting their structure and properties (Zherebtsov et al. 2018). Mechanical treatment of brown coals with oxidizing alkaline reagents and mineral salts can increase the yield of water-soluble humic substances, impacting the concentration of acidic functional groups in humic acids and enhancing their antioxidant activity, which in turn influences plant growth and development (Yudina et al. 2021). Additionally, the extraction of humic acid from lignite and bituminous coal through chemical pretreatment can lead to improved yields and changes in chemical characteristics, making them valuable for soil enrichment and green energy solutions (Fatima et al. 2021). Biotransformation of lignite with bacterial activity can result in the formation of humic acids with different structural properties, influencing their aromaticity, hydrophilic tendency, and content of functional groups, ultimately affecting their fertilizing value and positive impact on plants (Valero et al. 2018). The humic acid content of brown coals influences their fertilising value, their ability to improve soil quality and their positive impact on plants.

Humic acids have been extensively studied for their ability to form complexes with micronutrients, enhancing their availability to plants (Vikram et al. 2022). These organic molecules play a crucial role in improving soil structure, increasing water and nutrient retention capacity, and stimulating various biological processes in soils, such as organic matter decomposition and nutrient cycling (El-Aziz et al. 2020). Research indicates that humic acid-based products positively influence soil physical, chemical, and biological characteristics, including texture, cation exchange capacity, and nutrient availability, ultimately benefiting crop growth, plant hormone production, and yield (Tchaikovskaya et al. 2021). Moreover, studies have shown that humic substances exhibit high physiological activity for seed germination and can reduce the toxicity of pollutants in the environment, further highlighting their potential for enhancing plant growth and soil health.

Research into the chemical composition of lignite is crucial for understanding its potential applications across various fields. Studies have shown that lignite derivatives, such as humic acids, exhibit hybrid functionality due to the presence of diverse functional groups, enabling them to act as effective modifiers in different materials (Little 2015). Furthermore, the application of lignite-derived products in agriculture has been investigated, with findings indicating variable effects on plant growth, soil health, and microbial communities, emphasizing the importance of considering factors like soil type, application rates, and specific plant species (Lebedev et al. 2023). Additionally, lignite-derived humic acids have been utilized to enhance maize growth, yield, and nutrient uptake, showcasing the positive impact of lignite components on crop productivity and soil health (Жуланова, Глушанкова 2022). Moreover, the conversion of lignite into valuable chemicals and high-performance carbon materials demonstrates the potential for clean and efficient lignite utilization in producing value-added products (Khan et al. 2014). These collective findings underscore the significance of ongoing research into lignite's chemical composition to unlock its full potential in energy, agriculture, horticulture, and land reclamation applications.

The elemental composition of lignite varies significantly based on the degree of coalification, as supported by various research papers. In less carbonized coals, such as those transitioning from peat, the organic carbon content typically hovers around 60% (Li, Du 2022). However, in more advanced stages of coalification, the organic carbon content can reach up to 80%, while hydrogen content can account for up to 8% (Zhang et al. 2016). Additionally, the distribution of organic sulfur in coal is closely related to the metamorphic degree, with thiophenic sulfur content decreasing as the metamorphic degree decreases (Bambalov 2011). These findings highlight the dynamic nature of organic matter composition in lignite, showcasing how the degree of coalification influences the elemental makeup of the coal. The limit and average elemental composition values of humic lignite are shown in Table 10.

Table 10. Average and limit values for the elemental composition of lignite.

Type of coal	Average values			Limit values		
	C	H	O	C	H	O
	[% by weight].			[% by weight].		
earthy coals	63-70	5-6.5	30-32	60-70	4.6-7	30-20
pyropoissite coals	72-76	7-10	10-7,5	70-80	7-12.5	13-8
matt coals	71-73	5-6	22-18	70-75	5-6.5	25-15
pitch coals	74-78	5.2-5.7	18-15	70-80	5-6.5	20-13

Source: based on Kalembasa and Tengler (1992).

The nitrogen content of the organic matter of lignite is most often 0.8%-1.4%. The sulphur content of lignite is usually higher than that of hard coals. It is generally accepted that the sulphur content averages 1-4%.

Lignite consists of a number of group components. These mainly include humic acids, hymatomelanes, fulvic acids and bitumen. Humic acids are not only the main component of lignite, but also the most important component with regard to suitability for agricultural use. They are multi-molecular, polyfunctional and amorphous organic acids. They are characterised by a common type of structure, but show some differences depending on their origin.

Humid-acid content in low-carbon solid fuels is relatively high, up to 90%, while their content in peat can reach up to 50%. However, in general, this figure is usually around 70%. As carbonisation occurs, humic acids transform into compounds known as humates. The physico-chemical characteristics of domestic lignite are shown in Table 11.

Table 11. Chemical characteristics of domestic lignite.

Origin of coal - deposit	Type - petrogra-fic	Content ash A^d [%]	Content volatile parts V^{daf}	Elemental composition			Acid content humin	
				C^{daf} [%]	H^{daf} [%]	$S+O+N^{daf}$ [%]	KH^d [%]	KH^{daf} [%]
Turów Konin	earthy xylite	13.5	50.6	68.5	6,.9	24.6	35.1	40.6
	fibrous	1.6	71.7	60.0	6.4	33.6	18.3	18.6
Konin	earthy	22.0	56.3	70.6	6.9	22.5	51.1	65.5
Kaławsk	earthy	19.9	58.2	69.9	7.6	22.5	56.1	70.0
Babina	earthy	11.2	56.3	66.4	7.6	26.0	63.3	71.3
Sieniawa	earthy							
	-xylite	7.3	54.7	65.2	5.6	29.2	59.2	63.9
Rogoźno	earthy	17.1	57.9	64.5	7.6	27.9	64.7	78.0
Legnica	earthy	8.5	58.2	68.9	7.2	23.9	56.5	61.7
Belchatow	earthy	11.2	56.9	70.2	7.8	22.0	50.1	56.4

Source: based on Kalembasa and Tengler (1992). Note: d – dry state, daf – dry and ashless condition.

The properties of humic acids, separated from lignite with different degrees of coalification, show that their structure changed systematically during the coalification process. As the degree of carbonisation in humic acids increased, so did the C-element content and aromaticity, ring condensation index, molecular weight and viscosity of alkaline solutions, while the number of side chains, functional groups, ether bonds and the degree of dispersion decreased (Burdon 2001).

Humic acids are composed mainly of carbon, hydrogen and oxygen, with small amounts of nitrogen and sulphur. The elemental C content ranges from 56-70%, hydrogen 3.3-6.2% and oxygen 24-33%. Nitrogen is usually present in amounts of less than 3%, up to 5% in exceptional cases. As a general rule, sulphur content does not exceed 2%, while in humic acids derived from high-sulphur coals it can be as high as 10%. It occurs most often as a heteroatom or in the form of $-SO_3H$ groups (Kowalski, Rosiński 1957). Carbon and hydrogen are present in ring connections, aliphatic chains and as components of functional groups. Oxygen can occur as heteroatoms in rings, as bridges or in functional groups, while nitrogen can take the form of heteroatoms or amide groups. Sulphur occurs most often as a heteroatom or in the form of $-SO_3H$ groups (Kowalski, Rosiński 1957).

The elemental composition of humic acids is variable and depends on the degree of carbonisation of the lignite from which they were extracted. As lignite undergoes higher carbonization levels, the elemental C content increases while the hydrogen content, total oxygen, nitrogen, and sulfur content decrease (Tarhan et al. 2015; Valero et al. 2018). Additionally, a higher degree of carbonization results in an elevated C ratio (Fatima et al. 2021). The presence of hydrogen is likely a consequence of aromatic ring condensation (Li, Ding 2021). These findings suggest that the elemental composition of humic acids is intricately linked to the carbonization process of the lignite source, highlighting the importance of understanding the origin and processing of these organic materials for various applications in agriculture and environmental remediation.

The basic elements of the structure of humic acids are benzene- and pyridine-type aromatic rings, alicyclic rings, aliphatic chains, bridges and functional groups. Hydroaromatics and alicyclic rings containing oxygen or sulphur heteroatoms, furan and thiophene may also be present (Leenheer 2016).

The functional groups found in humic acids play an important role in the soil environment. They condition many properties of humic acids, such as hydrophilicity, acidic character and ion exchange capacity, among others. Of the functional groups, the oxygen ones are most important: -COOH, -OH, >C=O, and $-OCH_3$. The -COOH and -OH groups give human acids their particular ion-exchange characteristics. More than 25 per cent of the atoms in the structural unit of humic acids are believed to be in the form of active functional groups, while 75 per cent are the inactive part. These are mainly polyaromatic or bridge structures. The active functional groups disappear as the degree of carbonisation increases, thus losing their ion-exchange properties.

The structure of humic acids is complex and dependent on many factors. It depends both on the nature of the coal and on the type of transformation that the starting carbonaceous material underwent during the coalification process. The humic acid model proposed by Fuchs in 1933, is shown in Figure 19. This model illustrates an aromatic condensed system with benzopyrene as the central ring. This system has no side chains.

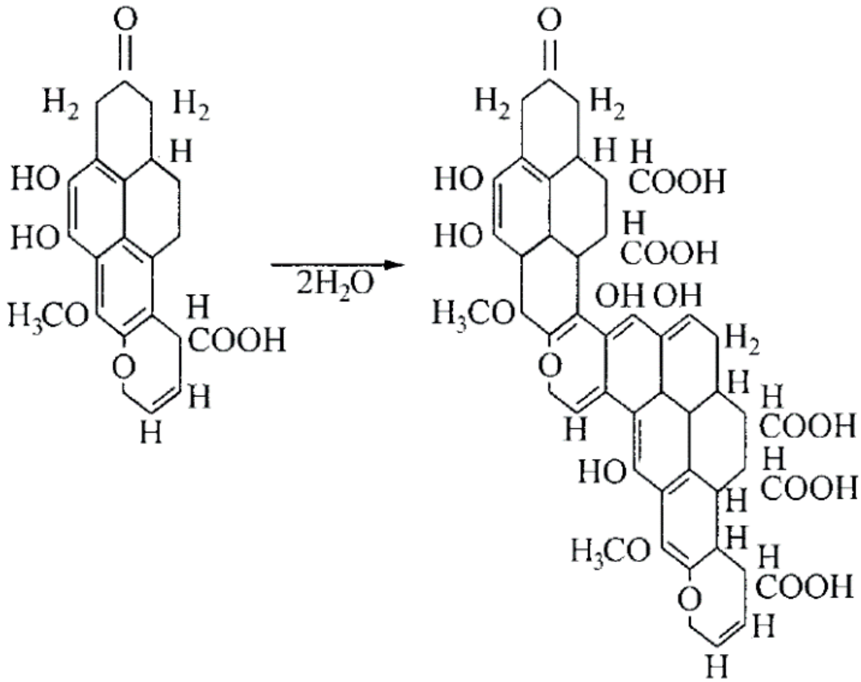

Figure 19. Humic acids model proposed by Fuchs (Al-Faiyz 2017).

In 1948 Dragunov proposed a model for a structure containing two-, or three-substituted aromatic rings, heterocyclic rings containing nitrogen, nitrogen in side chains and carbohydrate residues, as shown in Figure 20 (Al-Faiyz 2017). According to Gonet (1993), the major flaw of the proposed model is that all rings have oxygen substituents. This is ruled out by analyses of the oxidation products of humic substances with potassium permanganate.

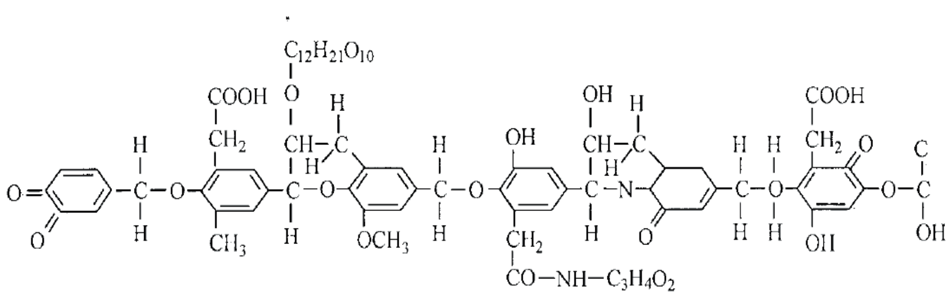

Figure 20. Model of linear structure of humic acids proposed by Dragunov in 1948. Source: based on the study by Al-Faiyz (2017).

Scientific evidence from the provided research papers indicates that the models of humic acids (HAs) are based on assumptions and do not offer a definitive representation of the actual structure of the basic structural unit of HAs. Various studies have attempted to understand the molecular structure of HAs through methods like membrane dialysis experiments and low-pressure size-exclusion chromatography (Capasso et al. 2020), transforming 2-D models into 3-D structures (Lijing et al. 2008), and computational modeling using molecular dynamics simulations (Petrov et al. 2017). These approaches have highlighted the complexity and challenges in accurately depicting the molecular structure of HAs, emphasizing the need for further research to gain a comprehensive understanding of these important organic substances in the environment (Piccolo 2002).

HAs exhibit complex interactions with bases and salts in aqueous solutions, leading to reversible reactions that reach equilibrium at specific concentrations (Dolenko et al. 2020). The reactions of HAs with alkaline earth metal salts of organic acids, such as calcium acetate, are primarily attributed to carboxyl groups within the structure of HAs (Singer, Huang 1990). Studies have shown that the biological activity of HAs is influenced by the mineralization of solutions, with the presence of mineral salts affecting the direction and intensity of the effects on biological organisms (Shaban, Mikulaj 1998). Additionally, the solubility of HAs is highly dependent on factors like pH and ionic strength, showcasing non-monotonous behavior in relation to pH changes and the influence of anionic surfactants on its solubility curve. These findings collectively support the notion that HAs interactions with bases, salts, and specific metal salts are intricate and can be attributed to distinct functional groups within the HAs molecules.

HAs exhibit significant ion exchange capacity, interacting with various metals like sodium, potassium, aluminium, iron, copper, manganese, cadmium, lead, and rare earth metals (Shoba, Chudnenko 2014). The ion exchange properties of HAs are influenced by factors like pH, temperature, and ionic strength, affecting the adsorption of metals such as Pb^{2+} (Madronová et al. 2001). Studies have shown that the relative abundance of metals in humic acids can vary, with some metals like lead being more prevalent than others like copper or cadmium (Li et al. 2001). Additionally, the ion exchange capacity of HAs can differ based on the atomic weight of the metal, with heavier metals generally exhibiting greater interactions, except for hydrogen. These findings underscore the complex nature of metal-humic acid interactions and the importance of considering various factors in understanding ion exchange processes.

An important feature of humic acids is their colloidal properties. Among these, the ability to absorb moisture is particularly important, a property possessed both by humic acids extracted from lignite and those originally contained in the soil.

In natural environments, humic acids are found in a highly swollen hydrogel state with a high water content. Such gels are the reason for the characteristic colloidal properties of brown coals. During the sorption of water vapour, there is a spatial expansion of the colloidal system, referred to as swelling. Water is incorporated into the colloidal lattice of humic acids. The swelling of lignite is caused by the swelling of humic acids (Rammler, Alberti 1972).

Humic acids in colloidal solutions exhibit a negative charge due to the partial dissociation of functional groups like -COOH and -OH, leading to colloid stabilization (Dolenko et al. 2020). The negative charge of humic acid molecules plays a crucial role in various interactions, such as adsorption on mineral surfaces and affecting the surface energy of soil particles (Schutt, Shukla 2020). Studies have shown that humic acids are electron donors with negatively charged surfaces, influencing their adsorption behavior and the overall stability of colloidal aggregates . Additionally, the presence of humic acids in solutions has been linked to increased electrostatic repulsion, further supporting the notion of negatively charged colloidal humic acid molecules . This negative charge and subsequent stabilization are essential characteristics of humic acids in colloidal systems, impacting various environmental processes and interactions.

3.5. THE FERTILISING VALUE OF LIGNITE AND ITS IMPORTANCE FOR SOIL HEALTH

Scientific evidence supports the agrochemical definition of lignite as a fertilizer rich in organic compounds, particularly humic acids, and containing macro and micronutrients (Kalaichelvi et al. 2006). Lignite-derived products have been shown to enhance nutrient uptake, increase crop yield, and improve soil health by chelating cations, buffering pH, and promoting beneficial soil bacteria and fungi (Filcheva et al. 2017). Additionally, humic acids extracted from lignite play a crucial role in mobilizing nutrients, preventing nutrient losses, and increasing plant enzymatic activities, ultimately enhancing crop yields (Klučáková, Pavlíková 2017). Studies have demonstrated that lignite-based products can positively impact soil fertility, improve nutrient availability, and promote plant growth, highlighting their potential as soil conditioners and fertilizers. These findings emphasize the beneficial effects of lignite in enhancing the physical and physico-chemical properties of soils when used for fertilization, supporting its role as an effective agricultural input.

The essential nutrient content varies considerably, as indicated by the data in Table 12. Lignite also contains essential micronutrients for plants, as evidenced by studies showing that humic acid extracted from low-grade coal can enhance soil micronutrient availability (Tang et al. 2021). The primary component of lignite, however, is carbon, with a content of 63-78%, including humic acids (18.3-64.7%). The extraction of humic acids from lignite using a mixture of NaOH and KOH results in higher oxygen/carbon and nitrogen/carbon ratios, promoting the release of nutrients like potassium, iron, and nitrogen beneficial for plant growth. Furthermore, coal-derived humates, rich in humic acids, have been studied as organic fertilizers, with variations in properties affecting their growth-stimulating effects on plants, suggesting that the quality and amount of humic acids play a crucial role in promoting plant growth (Li, Yuan 2021). Therefore, the high humic acid content in lignite not only stimulates the formation of soil tubercles but also contributes to providing essential micronutrients and promoting plant growth. Together with divalent cations, they make these tubercles extremely hard.

Table 12. Macronutrient content of lignite.

Component	Macronutrients		Micronutrients	
	according to Kalembasa and Tengler (1992) [mg/dm³]	according to Mazur (1996) [mg/kg]	according to Kalembasa and Tengler (1992) [mg/dm³]	
Total nitrogen	—	420-590	Manganese	10-20
Mineral nitrogen	20-50	—	Zinc	2-5
Phosphorus	10-20	0.18-0.95*	Molybdenum	0.5-1.0
Potassium	10-100	0.03-0.06*	Bor	2-5
Calcium	1500-2500	—	Iron	10-30
Magnesium	300-500	—		

Source: based on Maciejewska (1998). Note: * bioavailable ions.

Lignite holds potential beyond energy production. Research indicates that lignite-derived products can be utilized in agriculture to enhance soil fertility and promote plant growth (Little 2015). These products, rich in humic acid, can improve soil health by chelating cations, buffering pH, and fostering beneficial soil bacteria and fungi (Baloch, Labidi 2021). Additionally, humic acid extracted from lignite has been shown to enhance nutrient uptake in crops, increase enzymatic activities, and improve plant resistance, ultimately leading to enhanced crop yields (Kalaichelvi et al. 2006). Moreover, lignin, a component of lignite, has been explored for its electroactive properties in energy storage applications, showcasing lignite's versatility beyond traditional uses (Liu, Li 2022). Therefore, the multifaceted benefits of lignite in agriculture and horticulture highlight its potential as a valuable resource for sustainable agricultural practices and environmental conservation efforts.

Brown coal is rich in organic humic substances, such as humic acid and fulvic acid. These substances are natural organic complexes that contain a variety of functional groups, such as carboxyl, phenolic and amino groups (Yudina et al. 2021; Zherebtsov et al. 2022). Since there is a considerable amount of humic substances in lignite, it is a valuable source of these compounds.

The humic substances present in brown coal have many beneficial properties for plants and soils (Zhilkibayev et al. 2022). These substances positively impact soil quality and fertility by enhancing water retention capacity, stabilizing soil structure, promoting soil microbial activity, and influencing nutrient uptake and root architecture (Vikram et al. 2022).

Additionally, humic substances act as binders and retention agents, effectively retaining water in soils (Zherebtsov et al. 2021). This increased moisture retention capacity is particularly crucial in arid regions or during periods of water scarcity, aiding in sustaining plant growth and agricultural productivity (Fisha et al. 2021). The use of humic preparations from brown coal in soil management can significantly contribute to improving soil moisture levels, especially in dry areas or during water-deficient periods, thereby supporting plant growth and ecosystem sustainability.

In addition, humic substances in lignite affect soil structure by forming colloidal complexes that increase soil aggregation and improve soil permeability to water and air. This provides plant roots with better access to nutrients and allows them to grow more efficiently.

Brown coal is also a source of micronutrients, which are essential for plant growth and development. It contains elements such as iron, manganese, zinc, copper and molybdenum. These micronutrients play a key role in plant metabolic processes, such as photosynthesis, chlorophyll formation, enzyme synthesis and hormonal regulation.

An important feature of lignite as a fertiliser is its gradual release of nutrients. The humic substances in lignite are stable and undergo a slow process of biological decomposition. This means that nutrients are released gradually, providing plants with a constant and long-lasting source of nutrition. This works in contrast to some quick-release fertilisers, which can lead to excessive soil salinity and harm plants.

The fertilising value of lignite can be used in various aspects of farming, including field crops, horticulture and vegetable growing, as well as gardening and lawn care. Lignite fertiliser blends are used as organic and mineral fertilisers that provide nutrients, improve soil structure and promote healthy plant growth.

With the growing interest in sustainable agri-food production, the fertiliser value of lignite is becoming increasingly important. The use of lignite as a fertiliser can reduce the use of artificial chemical fertilisers, reduce soil erosion, improve water retention and protect the environment.

In the following subsections of this chapter, we will discuss specific techniques and methods for using lignite as a fertiliser in different areas of agriculture and present scientific results that confirm its positive effects on soil and plants.

On the basis of research results published by numerous authors, we can conclude that lignite has a positive impact on plant growth, appearance and yields when used as a fertiliser. This is mainly explained by the properties of lignite, which are similar to those of soil humus.

Different varieties of lignite can be used to fertilise soils, such as earthy and xylitic coals, hard matt coals, glossy coals, pack coals and shale coals. However, the earthy variety, which has a high humic acid content, proved to be the most suitable. A variety of these coals are found in all domestic lignite deposits.

The individual deposits of the earthy variety, rich in humic acids, are differentiated by their mineral content and type. The elemental composition and structure of humic acids in soils can be influenced by the type of fertilizers applied, with mineral fertilizers enriching humic acids with aliphatic components and reducing their thermal stability (Завьялова et al. 2022). The organic matter, despite some variation from deposit to deposit, shows similar characteristics, making it possible to use these coals as a standard raw material for organo-mineral fertilisers. The xylitic variety of lignite, although somewhat poorer in humic acids, when subjected to appropriate chemical treatment – oxidation, hydrolysis, ammonia treatment, etc. – can also be a good raw material for obtaining such fertilisers. Lignite can also be blended with mineral fertilisers to obtain fertilisers with improved efficiency. Therefore, as there are many large reserves of lignite distributed across various regions of the country, it is now possible to make greater use of this resource as a fertiliser than in the past. The well-developed mineral fertiliser industry has created suitable conditions for their use in various combinations with lignite, in the form of multi-nutrient fertilisers with improved efficiency.

The suitability of lignite for fertiliser purposes is supported by its organic matter composition and specific properties. Lignite-derived products can enhance soil health, crop growth, and nutrient uptake due to their humic acid content and nutrient variability (Little 2015). Humic amendments improve crop performance, soil health metrics, and water use efficiency, promoting sustainable crop production in arid regions (Ma et al. 2022). Humic preparations from brown coals positively affect phytomass production and pod yield, with effects varying based on composition, substrate conditions, and plant species used (Fisha et al. 2021). Brown coal and biochars can be utilized to produce organo-mineral fertilizers, positively impacting grain yield in spring wheat (Mikos-Szymańska et al. 2019). Lignite's high humic acid content and nutrient-rich composition make it a valuable resource for enriching soil with humus compounds and essential nutrients, crucial for optimizing crop yields (Jia et al. 2020).

The organic matter of brown coal is characterised by a high content of oxygen functional groups and readily oxidisable forms of the element C with the release of carbon dioxide and some heat. In addition, the substance contains a number of nutrients, such as calcium, magnesium, iron, sulphur, and the micronutrients zinc, copper, manganese, molybdenum, boron. The content of nutrients and trace elements in 1 dm^3 of brown coal is as follows: nitrogen in the form of ammonium and nitrate, 20-50 mg; phosphorus, 10-20 mg; potassium, 10-100 mg; magnesium, 300-500 mg; calcium, 1500-2500 mg; sulphur in the form of SO_4^{2-} , 10-20 mg; iron, 10-30 mg; manganese, 10-20 mg; zinc, 2-5 mg; molybdenum, 0.5-1.0 mg; and boron, 2-5 mg (Bereśniewicz, Nowosielski 1976).

The most noteworthy of all the specific properties of lignite is its highly developed porous system, which allows it to absorb water, carbon dioxide and ammonia, exchange ions between the soil solution and the soil solid phase and complex heavy metals. The developed porous system plays an important role in mineral fertilisation. This is because it helps to their utilisation rate by plants, reducing their leaching into deeper soil and groundwater layers.

Brown coal is also pathogen-free and the humic compounds found in greater quantities than in the soil mitigate the toxic effects of high concentrations of salts, acids and other toxic compounds such as copper (Maciejewska 1993, Maciejewska et al. 1995). The weak acidic reaction of the lignite and the strongly developed surface may enhance the development of micro-organisms, which play an important role in soil processes. Brown carbon has a catalytic effect on the growth of bacteria, such as *Azotobacter, Clostridium* and on their nitrogen fixation. During the mineralisation of lignite in the soil, carbonic acid is formed, which acts on the mineral compounds that are difficult to dissolve, increasing their uptake by plants and the amount of carbon dioxide that is absorbed by plants (Kissel 1931). Lignite has also been found to improve the permeability of plant cell membranes, resulting in increased uptake of nutrients, especially nitrogen.

Brown carbon has a positive impact on the uptake of phosphorus and potassium by plants from soils and increases the assimilability of iron compounds, which, under its influence, are transformed from a form that is difficult to assimilate into a bioavailable form. The stimulating action of lignite consists of the formation of comprehensive connections between humic compounds and iron, which are in an absorbable form. This is important because the ratio of potassium to iron taken up by the plant determines its health. If this ratio is too low or too high, the plants will be subjected to chlorosis (Gumińska et al. 1973).

As a result of its buffering properties, lignite affects soils pH, reducing high concentrations of H^+ and OH^- ions (Musierowicz 1938). The buffering properties of lignite are explained by their saturation with hydrogen ions, which react with the hydroxide ions of alkaline solutions, on the one hand, and with metal cations on the other, leading to the neutralisation of the hydrogen ions of acidic solutions.

Scientific evidence from various research papers supports the fertilising properties of lignite through both direct and indirect effects. The direct impact is influenced by lignite's chemical composition, including fertilising elements, micronutrients, and humic acids, as highlighted in the study by Liu et al. (2023). Additionally, the presence of humic acids in lignite can enhance soil health and nutrient uptake by plants, as discussed in the study by Little (2015). The indirect effect of lignite stems from its porous structure, which promotes the development of beneficial microflora in the soil, crucial for plant nutrition, as indicated by Kocsis et al. (2018). These combined factors contribute to the overall fertilising properties of lignite, making it a valuable resource for enhancing soil fertility and supporting plant growth in agricultural settings.

Based on the results so far, we can conclude that suitably crushed lignite is a good organic-mineral fertiliser for the following reasons:

- increases the sorption capacity of soils significantly,
- increases field water capacity in soils,
- increases the content of readily available forms of nutrients in soils,
- improves and stabilises the soil reaction (Maciejewska 1993, Maciejewska 1994).

Using lignite as a soil improver offers the advantage of slow action, crucial for long-term soil fertility maintenance (Rashid et al. 2023). Additionally, lignite-fertilized soils show significantly reduced leaching of cationic nutrients like Ca, Mg, Fe, and Na, which is vital in decreasing soil and water pollution, leading to a more efficient utilization of nutrients from these fertilizers (Jiang et al. 2022). Biochar, a carbon-rich material, has also been shown to reduce soil nitrate leaching by 37.1% and increase soil phosphate retention by 20.8%, contributing to the control of non-point source pollution and enhancing nutrient retention in soils (Chen et al. 2023). Furthermore, enhanced efficiency fertilizers (EEFs) have demonstrated increased soil nutrients, crop yield, and nitrogen use efficiency while reducing nitrogen leaching and greenhouse gas emissions, highlighting the potential of EEFs in sustainable fertilization practices (Xu et al. 2023).

On the basis of previous research carried out both domestically and abroad, lignite can be considered as an organic fertiliser, permanently improving the physical, water and sorption properties of very light soils. It is to be expected that high-reclamation doses of lignite, applied to very light soils, will clearly improve their sorption capacity and field water capacity, and that the positive effect of high doses of coal may persist for a long time, e.g. for more than 10 years.

Recent studies have shown that fine lignite fractions are most useful for agriculture because of the greater and faster improvement in the water and physical properties of soils. The earthy fraction is mostly suitable for agricultural purposes.

When using high doses of lignite, the application rates of mineral fertilisers should also be increased, especially in the first year. Small doses of mineral fertiliser are sorbed by the sorption complex, a process markedly increased by the addition of carbon. As a result, plants could potentially suffer from a lack of nutrients, which, in turn, has a negative impact on crop yield.

3.6. HUMIC ACIDS IN BROWN COAL

Lignite, as a fossil raw material, exhibits a distinctive humic acid content due to its low degree of carbonization, leading to a relatively high concentration of humic acids compared to other coal types (Tarhan et al. 2015). Various methods have been explored to extract humic acid from lignite, such as alkali extraction and catalytic oxidation, resulting in increased humic acid yield and value addition to lignite (Valero et al. 2018; Lu et al. 2020). Studies have shown that humic acid extracted from lignite can be fractionated based on molecular weights, with larger molecules containing higher proportions of aromatic structures and alkyl carbons, while smaller molecules exhibit more acidic groups like hydroxy and carboxyl (Kurniati et al. 2017). Additionally, the formation of solid humic acid from lignite through ion exchange methods has been successful, showcasing the versatility of lignite as a source of humic substances.

Humic acids are complex organic compounds with a high molecular weight, formed through the decomposition of organic matter like plants via biochemical processes (Valero et al. 2018; Linkevich et al. 2021; Piccolo 2002). The humic acid content found in brown coals can be attributed to their origin from plant material that has not undergone extensive carbonization processes, thus retaining a significant amount of humified organic matter (Fatima et al. 2021). Studies have shown that the extraction of humic acid from brown coals results in enhanced yields, indicating the presence of substantial organic components in these coals. Additionally, the molecular-level analysis of humic acids from different sources reveals variations in the degree of humification, molecular weight, and aromaticity, further supporting the notion of humic acids being intricate compounds derived from organic material undergoing decomposition processes.

Humic acids have many important properties and are highly significant in various fields. Their main role is to transport organic matter, which influences soil fertility and plant health. They are able to retain and release nutrients, regulating their availability to plants. Humic acid improves the soil structure, increasing its water retention capacity. This is particularly important for irrigation and in maintaining soil stability.

Lignite, with its high humic acid content, has great potential as a fertiliser raw material. Thanks to its properties, it can be used to improve soil structure, increase soil fertility and as a carrier of plant nutrients. In addition, humic acid has a stimulating effect on plant root development, enhancing plant growth and health.

It is worth noting that the humic acid content of lignite can vary depending on the specific deposit. These differences may be explained by various factors, such as the composition of the plant material, sedimentation, and diagenesis conditions. Therefore, a thorough analysis of the chemical composition of lignites, including their humic acid content, is important to determine their potential and possible use in various sectors, including agriculture, horticultur,e or soil reclamation.

In summary, lignite is characterised by its specific content of humic acids, which have a significant impact on soil fertility, plant health and ecosystem functioning. These properties can be highly beneficial, both in the context of sustainable agricultural production and in areas related to environmental protection and the restoration of degraded land.

3.7. IMPORTANCE OF LIGNITE FOR THE ENVIRONMENT

Lignite is important for the natural environment for several reasons. **Firstly**, the use of lignite as an energy source helps to reduce greenhouse gas emissions compared to other fossil fuels, such as coal or natural gas. The combustion of lignite emits lower amounts of carbon dioxide per unit of energy produced, helping to reduce the greenhouse effect and the negative impact on the climate.

Secondly, lignite can have a positive impact on the rehabilitation of degraded land. During the process of lignite mining, natural vegetation is often removed or destroyed and the landscape is modified. However, there is the potential to rehabilitate these areas with lignite once mining has ceased. It can be used as a component of organic matter to restore soil fertility, restore biodiversity and re-establish the natural ecosystem.

Thirdly, lignite can be used as an organic fertiliser in agriculture and horticulture. Thanks to its rich organic components and minerals, lignite can improve soil structure, increase water retention capacity and provide nutrients for plants. The use of lignite as an organic fertiliser can lead to an increase in yields, an improvement in crop quality and a reduction in the use of artificial chemical fertilisers, thus helping to reduce the negative impact on the environment.

Lignite can also be used **in soil remediation processes** on contaminated sites by absorbing chemical pollutants, for example. Its porous structure and ability to bind substances can help to clean soils and restore them to a healthy state.

Finally, lignite can provide **an alternative source of raw materials** for industry. Some of the components of lignite can be used to produce building materials, mineral fertilisers, chemicals or coal products. The use of lignite as a raw material can contribute to sustainable development, reducing the consumption of other natural resources and mitigating the negative impact on the environment.

All these aspects underline the importance of lignite for the natural environment. Its use and rational management can help to reduce negative climatic effect, improve degraded land, increase the efficiency of agricultural production and reduce the consumption of other natural resources. However, a sustainable and responsible approach is also important to ensure that the environment is protected and the negative effects of lignite mining are minimised.

3.7.1. Absorption of pollutants by lignite

Lignite has been extensively studied for its ability to remove heavy metals like cadmium (Cd) and copper (Cu) from aqueous solutions due to its high adsorption capacity, making it a promising material for soil remediation processes on contaminated sites (Schlögl et al. 2023). Research has shown that lignite can rapidly adsorb significant amounts of Cd and Cu, with adsorption occurring heterogeneously on multilayer surfaces, indicating the potential for pollutant removal through cation exchange and complexation with specific functional groups (Bilias et al. 2021). Additionally, a contaminated soil remediation agent incorporating lignite as a component has been developed, highlighting lignite's role in soil remediation processes. These findings support the idea that lignite's absorption process involves the adsorption of pollutant particles on its surface or within its pores, making it a valuable resource for addressing contamination in soils through immobilization of heavy metals (Li, Wu 2023).

Research on lignite highlights its significant potential for adsorption due to its large specific surface area and porous structure. Studies show that lignite derivatives, such as humic acids, possess hybrid functionality with various functional groups, enhancing their reactivity and ability to modify materials (Lebedev et al. 2023). Additionally, investigations into coal macerals reveal that different maceral groups exhibit varying pore structures affecting gas adsorption capacities, with vitrinite and inertinite enriched samples showing distinct pore characteristics (Jia et al. 2023). Molecular dynamics simulations focusing on lignite surfaces demonstrate that oxygen-containing functional groups influence water molecule dynamics and adsorption, with carboxyl groups identified as preferential adsorption sites (You et al. 2019). Furthermore, analyses of Belovo coal confirm the determination of specific surface and porosity, crucial factors for adsorption processes (Kozyreva, Nepeina 2019). Overall, these findings collectively support the assertion that lignite's specific surface area and porous structure play a vital role in facilitating chemical adsorption processes.

Research from multiple studies provides evidence supporting the adsorption mechanism of contaminant molecules on lignite surfaces through various interactions. Water molecules tend to aggregate around functional groups on lignite, with hydrogen bonds playing a dominant role in the interaction (Gao et al. 2017). Nonylphenol ethoxylate (NPEO10) adsorption on lignite is driven by polar interactions, affecting the hydrophobicity of the coal surface and repelling water molecules (He et al. 2018). Oxygen-containing functional groups on lignite interact with gases like CO_2 through different energy levels, with carboxyl groups exhibiting the highest adsorption energy (Lun et al. 2022). The removal of inherent minerals from lignite reduces hygroscopic performance but exposes more functional groups, enhancing water adsorption due to increased interaction forces (Teng et al. 2023). Additionally, magnetically modified lignite shows improved adsorption of heavy metal ions through chemisorption and specific vibrational interactions (Di et al. 2022). These findings collectively demonstrate that electrostatic forces, chemical bonds, and van der Waals interactions play crucial roles in attracting contaminant molecules to lignite surfaces. Lignite can adsorb different types of pollutants, such as heavy metals, pesticides, organic compounds or chemicals. Soil treatment with lignite can help to reduce the concentration of these substances and improve soil quality.

The adsorption process depends on many factors, such as the type of contaminant, its concentration, soil pH, temperature, type of lignite and its physicochemical properties. It is therefore important to carefully match the type and properties of the lignite to the type of contaminant and soil conditions in order to achieve effective adsorption.

The adsorption of pollutants by lignite has many environmental benefits. The most noteworthy of these benefits is its role in removing or reducing harmful substance concentrations in soils, which can affect plant, animal and human health. In addition, by adsorbing pollutants, lignite can protect groundwater and surface water from contamination.

However, it is worth noting that the adsorption of contaminants by lignite is not a permanent process and that the saturation of lignite particles with contaminants may occur. It is therefore important to regularly monitor and replace lignite in reclamation processes to maintain adsorption efficiency.

Lignite is therefore a valuable tool in environmental protection and remediation of contaminated sites. Its ability to adsorb contaminants allows it to improve soil and water quality, which is important for the health of ecosystems and people.

3.7.2. Heavy metal binding process in mineral-organic combinations

The fixation of heavy metals in mineral-organic combinations is a multifaceted process involving interactions between mineral and organic components in soils. Various mechanisms contribute to the binding of heavy metals in these combinations, such as the presence of colloidal particles of soil organic matter, clay silicates, metal hydroxides, and microorganisms that serve as important adsorptive surfaces for heavy metals (Aljumaily, Al-Hamandi 2022). Organic matter, including fulvic and humic acids, forms complexes with heavy metal ions, affecting their mobility and solubility in soils (Tan et al. 2018). Studies on the immobilization of heavy metals in contaminated soils have shown that combinations of organic and mineral materials can effectively reduce the mobility of heavy metals through processes like adsorption and complexation (Nwachukwu et al. 2021). Additionally, the addition of innovative organic-mineral mixtures to soils has been found to alter the mobility of heavy metal ions, highlighting the role of substrate properties and sorption surfaces in controlling heavy metal behavior (Wu et al. 2015).

Adsorption on the mineral surface: Heavy metal particles can adsorb on the surface of mineral particles in soils, such as clays, iron oxides or hydroxyapatite. The surface of mineral particles has charged sites to which heavy metal ions can be attracted. Adsorption is a physical process and depends on factors such as soil pH, metal ion concentration, mineral type and specific surface area.

Complexation with organic substances: Organic compounds in soils, such as humic acid, pectin, amino acids or humic acids, can form complexes with heavy metals. Complexation consists of the formation of permanent chemical bonds between metals and functional groups of organic compounds. Organic substances act as chelating agents that stabilise heavy metals and prevent their biological activity.

Ion exchange: Some minerals in soils, such as montmorillonite, illite or vermiculite, are able to exchange ions. Heavy metal molecules can replace lower-energy ions in the structure of these minerals. This process leads to the binding of heavy metals in the crystal lattice of the minerals.

Precipitation: Precipitation is the process by which substances dissolved in solution form insoluble precipitates or solid particles. It is the result of a chemical reaction between two or more components of a solution that leads to the formation of new compounds of limited solubility.

In the case of heavy metal binding in mineral-organic combinations, precipitation can occur when metal ions react with mineral or organic substances in soils to form insoluble compounds. These compounds, in the form of sediment or particulate matter, settle in soils and become difficult for living organisms to access.

Precipitation can result from various chemical reactions. For example, a reaction between a heavy metal and a sulphate can lead to the precipitation of an insoluble metal sulphate. Similarly, the reaction between the metal and carbonate can precipitate an insoluble metal carbonate. Precipitation can also occur when the concentration of a substance exceeds its solubility in a given environment.

Precipitation is important in the context of heavy metal binding, as it results in the conversion of these compounds into forms that are more difficult to solubilise and less toxic to living organisms. Insoluble sediments settle on the soil surface or form mineral components that serve as long-term storage for heavy metals. This reduces the risk of their migration into groundwater or surface water, helping to protect the environment and human health.

Precipitation therefore plays an important role in the natural processes of purification and retention of heavy metals in soils, contributing to the balance and health of ecosystems.

In some cases, heavy metals can precipitate as insoluble compounds, such as sulphides, carbonates or phosphates. Precipitation is the result of a chemical reaction between metals and mineral or organic substances in soils. The precipitated compounds are hardly accessible to living organisms and are stable forms of metal compounds.

The binding of heavy metals in mineral-organic combinations is important for environmental protection, as it prevents their migration and availability to living organisms. The processes described above, such as adsorption, complexation, ion exchange and precipitation, play a key role in reducing the risks associated with the toxic effects of heavy metals on ecosystems and human health.

LIGNITE FERTILISER BLENDS

As a valuable raw material found in various regions of the world, lignite is becoming increasingly important in the field of sustainable agriculture and environmental protection (Maciejewska et al. 2022). Its agricultural use as an ingredient in a fertiliser mix has many benefits for both soils and crops (Maciejewska et al. 2024). In this chapter, we will introduce the innovative solution of lignite fertiliser blends, discussing their importance, benefits and the techniques used in their production.

According to the agrochemical definition, lignite is a fertiliser that is a source of organic compounds with a high proportion of humic acids and, to a lesser extent, macro- and micronutrients. When used as a fertiliser, lignite improves the physical and physico-chemical properties of soils. The essential nutrient content varies considerably. Lignite also contains micronutrients essential for plant fertilisation. The primary component, however, is carbon, with a content of 63-78%, including humic acids (18.3-64.7%).

As previously mentioned in Chapter 3, lignite, as a rich source of organic carbon, has many beneficial properties that enhance soil fertility and plant development. Lignite fertiliser blends combine these benefits with other fertiliser components to create a comprehensive solution that stimulates optimum plant growth and yields, while contributing to the sustainable management of natural resources.

The organic matter contained in lignite is characterised by a high degree of polymerisation and condensation. This limits the direct participation in biological processes of a significant proportion of the functional groups of this substance, primarily the oxygen groups that largely determine the reactivity of carbon. It is therefore desirable to modify lignite in order to partially degrade the humic substance it contains. This modification consists in treating lignite with various chemical compounds, such as potassium or sodium hydroxide, ammonia, hydrochloric acid, nitric acid, phosphoric acid, sodium bisulphate solution, magnesium, iron, zinc or manganese compounds (Augustyn 1980).

The chemical treatment of lignite is aimed at increasing the content of water-soluble components and soil electrolytes and increasing the amount of oxygen functional groups. Loosening the lignite structure increases the number of active centres capable of metal complexation reactions. Metal-humate complex linkages are then formed, which play an important role in biological processes (Niklewski et al. 1971).

Fertilizer mixtures incorporating lignite have been shown to enhance soil fertility and improve soil structure and water retention, crucial aspects for sustainable agriculture (Rashid et al. 2023; Adeli et al. 2023; Maciejewska et al. 2024). Lignite serves as an effective nutrient carrier, aiding in the provision of essential nutrients to plants for optimal growth and development (Lei et al. 2023; Patel et al. 2022). Additionally, the application of lignite-based fertilizers has been demonstrated to extend the release of nitrogen, reducing losses such as NH_3-volatilization, NO_3-leaching, and N_2O -emission compared to conventional urea fertilizers, thus promoting a balanced ionic composition in plants (Rashid et al. 2021). The use of lignite in fertilizer formulations not only supports soil health but also ensures that plants receive the necessary nutrients over an extended period, contributing to sustainable agricultural practices.

However, lignite fertiliser blends are not only beneficial for plants, but also for the environment. The use of lignite as a fertiliser ingredient represents a sustainable use of this raw material, reducing the negative environmental impact that can be caused by its extraction for energy purposes.

In the following chapters, we will discuss techniques for the production of a fertiliser mixture from lignite, pointing out the benefits for plants, the sustainable use of lignite and current research and development in this field. We will also present practical examples of the use of a lignite fertiliser mix in different crops to demonstrate the full potential of this innovative solution in agriculture.

Lignite fertiliser blends open up new perspectives for agriculture, enabling the simultaneous supply of nutrients to plants and the efficient use of lignite.

4.1. HUMIC-MINERAL MIXTURES

Humic-mineral mixtures represent an innovative approach to crop fertilization, combining the synergistic effects of organic substances and minerals to enhance soil fertility and crop efficiency. These mixtures typically consist of humic substances, which are organic components, and minerals, creating a complex fertilizer blend with diverse benefits for plant growth and development (Zhilkibayev et al. 2022; Pavlovich, Strakhov 2018; Xiong et al. 2023). Research indicates that humic substances play a crucial role in regulating metabolic processes in plants and soil, improving nutrient bioavailability, and acting as growth promoters, while minerals contribute essential macro- and microelements necessary for plant nutrition and development. The combination of humus and minerals in these mixtures can lead to improved sowing quality, enhanced germination, accelerated biomass growth, increased fruiting periods, and overall higher crop yields, showcasing the effectiveness of humic-mineral blends in sustainable agriculture practices.

Humin, an organic substance resulting from the decomposition of organic matter like plants and agricultural waste, is rich in humic acid and fulvic acids, as highlighted in (Weber et al. 2023; Velasco Calderón et al. 2022). It possesses unique chemical properties, with aromatic structures dominating over aliphatic ones and hydrophobic fractions being prevalent, contributing to its resistance to further treatment and its role in soil carbon sequestration (Weber, Jamroz 2022). On the other hand, minerals, a source of essential nutrients like nitrogen, phosphorus, potassium, and trace elements, are crucial for proper plant growth and development (Liu et al. 2022). The formation of humins, observed during the acid-catalyzed dehydration of biomass-derived molecules, further underscores the intricate relationship between organic substances like humin and mineral components in the environment (Filiciotto et al. 2022).

Humic-mineral blends combine these two components for a synergistic effect. Humin reacts with minerals to form humic-mineral complexes, which are able to increase water retention, retain soil nutrients and stimulate soil microbial activity. This makes it easier for plants to access nutrients and enhances soil fertility and its ability to support healthy crops.

These fertilisers are obtained from a chemical reaction in which alkalis interact with lignite. During the reaction, the macromolecules of the humic substance contained in the carbon are depolymerised into soluble structures. An example of a humic-mineral fertiliser is the product obtained by treating lignite with ammonia. This results in an increase in the amount of compounds with soluble structures and an enrichment in nitrogen in lignite. According to various studies (Tengler, Kalembasa 1986), humic-mineral fertiliser, applied at a rate of 1.4 $x10^3$ kg/ha, leads to better results than lignite alone.

Humic-mineral fertilisers can also be obtained by treating crushed lignite with a sodium or potassium hydroxide solution.

An alkaline humic fertiliser is then obtained, containing mainly sodium or potassium salts of humic acids. Such fertiliser can only be used under plants that tolerate high soil pH. Another example of a humic-mineral fertiliser is humic-nitrogen-phosphorus fertiliser. This fertiliser has a greater impact than ammonium nitrate and superphosphate (Brodowska et al. 2022). Applied to light, sandy clay and heavy soils, it has proven beneficial for many cultivated plants, such as oats, barley, rye, faba bean, rapeseed, and potatoes. The increase in yield, depending on the soil type and crop grown, was 4-18% (Czekała, Jastrzębski 1971). Humic acids, which are a key component of humic-mineral fertilizers, have been shown to improve the efficiency and effectiveness of nitrogen and phosphorus fertilizers. According to Brodowska et al. (2022), humic acids enhance the efficiency of fertilisers and prolong their active impact, reduce nitrogen losses, and accelerate nitrogen uptake and utilisation by plants. Additionally, humic acids, by forming complexes with cations present in the soil, improve the phytoavailability of phosphorus, magnesium, iron, and zinc. This suggests that humic-mineral fertilizers containing both nitrogen and phosphorus can be more effective than standalone ammonium nitrate and superphosphate fertilizers. In turn, various studies provide evidence that humic substances increase the soil's water and heat holding capacity, improve its structure, enhance the microbiological activity of the soil, and thereby induce more intensive uptake of macro- and micronutrients by plants (Canellas, Olivares 2014; Nardi et al. 2021; Maji et al. 2017; Bezuglova et al. 2019). They can improve soil structure by enhancing aggregation and porosity (Canellas, Olivares 2014; Nardi et al. 2021; Tiwari et al. 2022). Humic substances also stimulate the growth and activity of soil microorganisms, including bacteria and fungi (Maji et al. 2017; Bezuglova et al. 2019) This increased microbial activity can lead to more efficient cycling and availability of macro- and micronutrients for plant uptake (Canellas, Olivares 2014; Bezuglova et al. 2019).

Specifically, humic substances:

- Increase water-holding capacity and improve soil moisture retention (Canellas, Olivares 2014; Nardi et al. 2021; Tiwari et al. 2022);
- Enhance soil thermal properties and insulation, regulating soil temperature (Canellas, Olivares 2014; Nardi et al. 2021; Tiwari et al. 2022);
- Improve soil structure, aggregation, and porosity, leading to better aeration and drainage (Canellas, Olivares 2014; Nardi et al. 2021; Tiwari et al. 2022);
- Stimulate the growth and activity of beneficial soil microbes, including bacteria, fungi, and earthworms (Canellas, Olivares 2014; Nardi et al. 2021; Maji et al. 2017; Bezuglova et al. 2019);
- Increase the availability and uptake of essential macro- and micronutrients by plants (Canellas, Olivares 2014; Nardi et al. 2021; Maji et al. 2017; Bezuglova et al. 2019).

Humic-mineral fertilisers are characterised by their high content of biologically active organic components that are soluble in water and exhibit bio-stimulant effects. The characteristics of humic and humic-mineral fertilisers produced from lignite from KWB *Konin* are shown in Table 13.

Table 13. Characteristics of humic and humic-mineral fertilisers produced from coal lignite from the Konin Mine.

No.	Type of fertiliser	Status concen tration	Characteristics	Content				
				W*	Corg	N	P_20_5	K_20
				[% by weight].				
1	humic alkaline	liquid	lignite + NaOH	86	7	—	—	—
2	humic alkaline	solid	fertiliser 1 dried at less than 80°C	20	40	—	—	—
3	humic inert	liquid	fertiliser 1 neutralised with HNO_3	76	7	0.5	—	—
4	humic inert	solid	fertiliser 3 dried at less than 80°C	20	40	1.7	—	—
5	humic-mineral complex	liquid	fertiliser 3 enriched with with K_2SO_4, urea, and di-ammonium phosphate	56	13	3.0	2.9	4.2
6	humic-mineral complex	solid	fertiliser 5 dried at less than 80°C	20	25	8.2	6.9	10.0
7	humic-mineral phosphorus-potassium	solid	fertiliser 4 mixed with triple superphosphate with water, potassium chloride or an equivalent amount of fertiliser 3	20	8	—	17.8	16.5

Source: based on Kalembasa and Tengler (1992). Note: * W - moisture content.

There are many benefits of using a humic-mineral mix. **Firstly,** they improve soil structure, especially in sandy or clay soils, which struggle to retain water and nutrients. Improved soil structure translates into greater water retention, which is crucial for plants, especially during periods of drought.

Secondly, humic-mineral mixtures increase the availability of nutrients for plants. Humin is able to form complexes with mineral ions, preventing their loss through leaching and enabling the gradual release of nutrients in a plant-available form. This ensures that the plants have continuous access to essential nutrients for a longer period, contributing to their healthy growth and greater yields.

Thirdly, humic-mineral mixtures stimulate the activity of soil micro-organisms. Humin provides organic matter that serves as a nutrient for micro-organisms, such as bacteria and fungi. These micro-organisms are essential for the processes of decomposing organic matter and converting nutrients into plant-available forms. Increased microbial activity contributes to a healthy biological balance of soils and enhances their ability to absorb nutrients.

Humic substances, like those found in humic-mineral mixtures, offer **ecological benefits** by promoting sustainable agriculture practices and reducing the reliance on artificial chemical fertilizers (Zhilkibayev et al. 2022; Ahamadou et al. 2022). These natural compounds positively impact plant growth, soil fertility, and the bioavailability of nutrients, thus minimizing the need for synthetic fertilizers that can harm the environment (Hriciková et al. 2023). Additionally, the use of humic substances can enhance nutrient uptake by plants, stimulate various plant processes, and improve crop yield, all while being environmentally friendly and promoting soil health (El-Tahlawy, Ali 2022). By incorporating humic substances into agricultural practices, the negative environmental impacts associated with eutrophication and mineral loss from chemical fertilizers can be significantly mitigated, showcasing the ecological advantages of utilizing humic-mineral mixtures in farming systems (Bezuglova, Klimenko 2022).

The use of a humic-mineral mixture as a fertiliser requires appropriate techniques and methods to achieve optimum results in improving soil fertility and plant health. In this section, we will discuss these techniques and methods and present the findings that provide scientific evidence for the effectiveness of this mix. In addition, we will present practical tips for the rational management of humic-mineral mixes to maximise soil and plant benefits.

One commonly used technique is the direct application of the humic-mineral mixture to soils. This mixture can be spread or evenly distributed on the soil surface, and then gently mixed into the soil with a plough or other tool. This technique is effective in delivering nutrients and humic substances directly to soils, i.e. the area in which plants grow.

The humic-mineral mixture can also be **added to the irrigation system**. This mixture can be dissolved in water and administered to the plants through a drip system or sprayer. This method is particularly effective for greenhouse crops or hydroponic systems, where irrigation is carried out in a controlled and precise manner depending on the type of plants and their nutrient requirements.

Scientific research provides substantial evidence supporting the positive impact of humic substances on soils and plants. Humic substances, including humic acids and fulvic acids, enhance soil quality by improving water retention capacity, stabilizing soil structure, and promoting beneficial interactions with soil microorganisms (Zhilkibayev et al. 2022). Additionally, the application of humic substances has been shown to increase nutrient availability to plants, stimulate root development, and act as phytohormones, aiding in phosphorus acquisition and enhancing plant adaptation to stressful conditions (Vikram et al. 2022). Studies have also demonstrated that humic substances positively influence soil physical, chemical, and microbiological attributes, leading to improved soil microporosity and overall soil health, which can enhance plant resistance to environmental stressors (Pereira et al. 2022). These findings highlight the significant role of humic substances in sustainable agriculture practices, promoting soil fertility, plant growth, and environmental resilience.

In order to make the most of the humic-mineral mixture, it is important to manage this type of fertiliser rationally. Practical tips include appropriate dosing of the mix according to plant requirements, regular monitoring of soil composition, adjustment of fertiliser doses and maintaining a balanced ratio between mineral fertilisers and the humic-mineral mix. In addition, strict adherence to the manufacturer's instructions for the application and storage of the mixture is essential.

4.2. NITROHUMIN-MINERAL BLEND

The **nitrohumin-mineral mix** is another type of fertiliser that combines organic and mineral components.

Nitrohumin-mineral fertilisers are obtained by modifying lignite with nitric acid or a mixture of nitric acid and sulphuric acid. These fertilisers are biologically active substances that have a stimulating effect on plant growth. They are mainly used in the cultivation of vegetable and ornamental crops. They have a positive impact when optimal growing conditions are disturbed, especially when the pH of the substrate is incorrect, mitigating the negative effects of over-acidification, or when there is a micronutrient deficiency or excess (Augustyn et al. 1972).

The characteristics of lignite nitrohumin-mineral fertilisers are shown in Table 14.

Table 14. Characteristics of nitrohumin-mineral fertilisers from lignite.

Type of fertiliser	Content							
	pH H_2O	W	N[a]	P_20_5	K_2O	MgO	CaO	Na_2O
		[% by weight].						
nitrohumin-potassium	7.2	7.0	—	—	24.7	—	—	—
nitrohumin-sodium	6.8	9.7	—	—	—			14.1
nitrohumin-calcium	7.4	8.8	—			—	21.9	—
nitrohumin-magnesium	9.5	17.5	—	—	—	14.6	—	—
nitrohumin-urea	6.2	3.1	20.4	—	—	—	—	—
nitrohumin-complex	6.2	8.8	10,.3	6.7	14.0	2.7	—	—
nitrohumin-complex	7.6	7.5	8.0	9.0	13.5	—	—	—

Source: based on Augustyn (1984) and Kalembasa and Tengler (1992).

Research provides insights into the application techniques for nitrohumin-mineral mix, showing similarities to those used for humic-mineral mix (Mirzaei Varoei et al. 2023). The study by Oustan et al. demonstrated that nitrohumic acids (NHAs) extracted from different organic sources can serve as slow-release nitrogen fertilizers, with variations in extraction methods impacting nitrogen availability and extraction yields (Klop et al. 2012). Additionally, Weber and Jamroz (2022) outlined a detailed procedure for isolating the humin fraction, emphasizing the removal of soluble organic and mineral components to obtain high yields without affecting the humin's chemical structure (Weber, Jamroz 2022). These findings suggest that the application of nitrohumin-mineral mix can involve direct soil incorporation through surface spreading or mixing, similar to traditional humic-mineral mix application methods, highlighting the potential for enhancing nitrogen use efficiency and optimizing fertilizer production processes. Importantly, nitrohumin-mineral blends can be applied directly to soils by evenly spreading over the surface and mixing into the soil, or added to an irrigation system where it is dissolved in water and delivered to plants.

Scientific studies on the nitrohumin-mineral mix have shown that it can increase crop yields, improve soil structure and increase water retention capacity and nutrient availability. The mixture can also stimulate root development, plant growth and resistance to environmental stress.

Rational management of the nitrohumin-mineral mixture involves tailoring dosages to plant requirements, monitoring soil composition, and adjusting fertilizer rates, as supported by various studies. Research has shown that applying mineral fertilizers and nitrogen to bean crops can enhance soil properties, increasing humus and nitrogen content (Abdumannobovich et al. 2020). Additionally, nutrient management plans (NMPs) have been linked to improved adoption of nutrient management practices and reduced excess nutrient application in hog farms (Sneeringer et al. 2018). Furthermore, the use of nitrification inhibitors in poorly-drained soils can optimize nitrogen use efficiency and crop yields, emphasizing the importance of timing and rates of application (Habibullah et al. 2017). Moreover, on-farm trials with nitrification inhibitors and different nitrogen sources have demonstrated varying effects on corn yields and soil nitrogen availability, highlighting the need for localized fertilizer management considering annual weather variability (Chatterjee et al. 2016). Therefore, integrating these findings underscores the significance of precise dosing, continuous monitoring, and considering diverse mineral fertilizer sources to maintain nutrient balance for optimal plant growth.

Practical tips for using a nitrohumin-mineral mix also include taking into account the plants' soil pH requirements and taking care of optimal soil conditions, such as proper irrigation, erosion control and other management practices.

4.3. HUMIN-MICRONUTRIENT MIXTURES

Another type of fertiliser made from lignite is **humic-micronutrient fertilisers**. The need for such fertilisers arises from the increase in NPK mineral fertilisation and soil liming, which leads to a decrease in trace element content and the availability of such elements to plants. A number of studies on fertilisation needs, including (Czuba, Siuta 1976), have shown a significant deficiency of micronutrients such as copper, boron, manganese and molybdenum in soils. Micronutrient fertilisers in the form of organic complex compounds of the chelate type (with lignite as a natural chelator) are more effective than those in the form of inorganic micronutrient salts, especially on acidic soils.

According to these studies, the agronomic properties of humic-micronutrient fertilisers significantly increase yields and greatly improve yield quality.

Application techniques for the humic-micronutrient lignite mix are similar to those used for other fertiliser mixes. It can be applied directly to soils, through even spreading over the surface and by mixing it with the soil, or by adding it to an irrigation system, where it dissolves in water and feeds to the plants.

Scientific research on humic-micronutrient lignite mixtures has shown that they can increase crop yields, improve soil structure and increase water retention and micronutrient availability. These mixtures can also stimulate enzymatic metabolic processes and root growth, enhancing plant resistance to environmental stresses and improving yield quality.

Rational management of humic-micronutrient lignite mixtures includes appropriate dosing according to plant needs and monitoring of soil composition. It is also worth considering other available sources of micronutrients and adjusting fertiliser doses to maintain balance and avoid over-feeding plants.

Practical tips for using humic-micronutrient lignite blends include taking into account the plants' soil pH requirements, adjusting fertiliser doses according to the type of crop and using irrigation to effectively deliver nutrients to plant roots.

4.4. DELAYED-ACTION LIGNITE BLENDS

Delayed-action lignite mixtures are another type of fertiliser with the special property of gradually releasing nutrients in soils over a prolonged period. Delayed-action lignite mixtures, such as lignite-based slow-release nitrogen fertilizers (LSRNF), offer a sustainable solution for gradually releasing nutrients in soils over an extended period (Rashid et al. 2023). These mixtures, developed by impregnating urea on deashed lignite, have shown significant delays in nitrogen mineralization, with nutrient release extended to over 70 days, reducing NH_3 volatilization, NO_3 leaching, and N_2O emission compared to conventional urea fertilizers (Nazarbek et al. 2023). Additionally, slow-controlled release fertilizer coating agents made from lignite wax resin and humate have been scientifically formulated to provide long-acting and quick-acting coordination, conforming to the principles of 'fertilizer coated by fertilizer' and 'soil nourished by soil' while being environmentally friendly and cost-effective (Li et al. 2023). These lignite-based formulations demonstrate the potential for sustainable and efficient nutrient delivery in agricultural soils, contributing to improved soil health and crop productivity.

Lignite is also used for the production of delayed-action fertilisers on organic carriers. The production of this type of fertiliser consists in introducing a controlled amount of the fertiliser component into the organic carrier and 'encapsulating' its polymer. Two types of delayed-action fertilisers have been developed. One of these is the Mono fertiliser, which contains only nitrogen or potassium, while the other is the multi-nutrient fertiliser Uno, which contains nitrogen and potassium, or only nitrogen, and all macro- and micronutrients in amounts determined by the needs of fertilised plants (Nowosielski et al. 1983; Bereśniewicz, Kołota 1987; Struszczyk et al. 1983).

Delayed-action lignite blends are usually produced as granules or tablets, which contain nutrients encapsulated in a carbon matrix (Rashid et al. 2023). Scientific studies have demonstrated that these fertilizers can significantly reduce nitrogen losses compared to conventional urea fertilizers (Abhiram et al. 2022). Additionally, controlled-release fertilizers like Epox5 and Ver-1 have shown effectiveness in decreasing total nitrogen losses and improving plant growth, with Ver-1 outperforming other treatments in terms of dry matter yield and nutrient accumulation (Nazarbek et al. 2023). Encapsulated fertilizers, like those using carboxymethyl cellulose (CMC) and humic acid (HA), have been shown to control nutrient release effectively under various soil pH conditions, enhancing sustainability and environmental friendliness (Roy et al. 2023). Moreover, slow-release fertilizers produced from crop residues have been found to support active bacteria populations and promote plant growth, indicating their potential as biostimulants (Ehis-Eriakha et al. 2022). Overall, delayed-action lignite blends offer a range of benefits, including increased nutrient use efficiency, reduced leaching losses, improved soil structure, and sustained plant growth, making them particularly suitable for long-term crops requiring a steady nutrient supply.

Rational management of delayed-action lignite mixtures includes appropriate dosage according to the needs of crops and consideration of the length of the crop cycle. For perennial crops, these fertilisers can be applied at the beginning of the season at the correct doses, ensuring a gradual release of nutrients throughout the plant growth period.

Practical tips for using delayed-action lignite bellows include considering the nutrient requirements of crops, the type of crop and the length of the growth cycle. As always, it is recommended to monitor the composition of soils and carry out regular analyses in order to adapt fertiliser doses to the needs of plants and avoid under- or over-feeding.

4.5. LIGNITE ORGANIC-MINERAL MIXTURES

Organic-mineral blends from lignite are another type of fertiliser that is increasingly popular in sustainable agricultural production. These are complex formulations that combine both organic and mineral components, enriched with brown carbon.

Lignite can also be used to produce organic-mineral fertilisers (Maciejewska et al. 2022). These organic-mineral fertilisers should ideally consist of components with specific characteristics: a substance with high water retention capacity, an organic material with strong cation sorption abilities, and substances that can rapidly mineralise to provide essential nutrients to plants. Additionally, these fertilisers should be rich in calcium to counteract soil acidity. Calcium can be introduced through fertilisers or lignite ash, a beneficial industrial waste used in agriculture for soil conditioning and deacidification, enhancing soil properties. Lignite ash stands out for its calcium (12-14% CaO), magnesium (3.0-6.0% MgO), and various micro and ultra-elements (Fe, Mn, Zn, Cu, B, Mo, Se, U, Co, Ti), making it a valuable resource for agricultural applications (Portell et al. 2023; Gondek, Mierzwa-Hersztek 2023; Sager et al. 2023).

Initial attempts have been made to produce this type of fertiliser. These include *Complete R, Rekulter, Plonofoska J and Plonofoska W* and are produced at KWB Konin (Curyło, Jasiewicz 1996).

Complete R and Rekulter are fertilisers designed for the agromelioration of sandy soils and for the reclamation of degraded post-mining land and chemically contaminated soils. These fertilisers contain 80% organic matter, more specifically, lignite and peat in a weight ratio of 5:1 and macro and micronutrients. These fertilisers are spread evenly over the surface of the reclaimed area and mixed with soils using a disc harrow or cultivator, and then ploughed in.

These fertilisers should be applied at the following rates: 100 t/ha every 10 years for highly degraded soils, soilless land and very light soils; and 50 t/ha every 10 years for soils with less degradation, low humus content and defective granulometric composition. No additional mineral fertilisation is recommended in the first year after the fertiliser application. In the second year and beyond, mineral fertilisation should be adapted to the needs of the crops grown.

Plonofoska J is a strongly deacidifying organic-mineral fertilizer, recommended for use in autumn under winter cereals or in spring under legumes. 1 tonne of the fertilizer comprises: approximately 500 kg of crushed lignite, 200 kg of lime (CaO), 15 kg of nitrogen (N), 40 kg of phosphorus pentoxide (P_2O_5), 60 kg of potassium oxide (K_2O), 20 kg of magnesium oxide (MgO), 0.25 kg of copper (Cu), and a superabsorbent to increase the water retention capacity of the improved soil.

It is recommended to apply this fertiliser before plant vegetation at a rate of 1 t/ha for each crop. For poor or slightly degraded soils, annual application is recommended, especially if such soils have a low pH.

Plonofoska W is a fertiliser designed for pre-plant application in spring to soils low in organic matter; 1 t of fertiliser contains approximately: 350 kg of crushed lignite, 150 kg of lime (CaO), 60 kg of nitrogen (N), 40 kg of phosphorus (P_2O_5), 60 kg of potassium (K_2O), 20 kg of magnesium (MgO), 0.25 kg of copper (Cu) and a superabsorbent to increase the water retention capacity of soils.

It is recommended to apply this fertiliser once a year to soils that dry out easily and are poor in organic matter, in a dose of around 1 t/ha.

Organic-mineral lignite mixtures have been shown to offer significant benefits for both soils and plants. Research indicates that these mixtures enhance soil properties by improving soil structure, increasing water retention, providing organic matter, and supporting soil microbial activity (Sołek-Podwika et al. 2023; Wolny-Koładka et al. 2022). Studies have demonstrated that the application of lignite-derived humic products can lead to substantial improvements in soil properties and plant growth, with a single-time application at the beginning of each growing season yielding better results compared to split applications (Wolny-Koładka, Jarosz 2022). Furthermore, the use of humic amendments has been found to increase soil organic carbon, water storage, and soil enzyme activity, promoting soil health and nutrient availability for sustainable crop production in agricultural settings (Ma et al. 2022). These findings collectively highlight the synergistic benefits of organic-mineral lignite mixtures in enhancing soil quality and supporting plant growth.

Minerals like nitrogen, phosphorus, potassium, and trace elements are crucial for healthy plant growth and development (Saleem et al. 2023; Tripathi et al. 2022). These essential nutrients play vital roles in enhancing tolerance to abiotic and biotic stress, promoting normal growth when present in adequate levels, and causing abnormalities when scarce. Macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, along with micronutrients like iron, zinc, boron, copper, molybdenum, manganese, nickel, and chlorine, are necessary for various metabolic functions in plants. Adequate levels of these nutrients are essential for plant defense mechanisms, including the modulation of enzyme activity, root exudates, and microflora dynamics, ultimately contributing to systemic resistance and overall plant health. The balance and availability of these mineral elements are critical for sustainable agriculture and maximizing crop productivity in the face of increasing global food demand.

The integration of lignite organic-mineral mixtures into soil has been shown to significantly enhance soil fertility and subsequently boost crop production (Solek-Podwika et al. 2023; Adeli et al. 2023). These mixtures not only supply essential nutrients to plants but also introduce organic matter that plays a crucial role in improving root health, metabolic processes, and overall plant vigor (Jabborov et al. 2023). Moreover, the organic components in these mixtures contribute to increasing the soil's water retention capacity, a vital factor especially during drought conditions, allowing plants to better withstand and thrive in challenging environments (Ma et al. 2022). The combined effects of lignite organic-mineral mixtures on soil fertility, nutrient availability, and water retention highlight their potential to support sustainable agriculture by promoting healthier plants and increased crop yields.

Lignite organic-mineral mixtures can be used in various forms, such as pellets, liquid concentrates or as components of a fertiliser mixture to be dispersed onto soils. It is important to dose and apply the fertiliser correctly, taking into account the needs of plants, the type of soil and the specific objectives of agricultural production.

Research on organic-mineral lignite mixtures is continuing in order to better understand the mechanisms of action of these fertilisers on soils and plants and to determine the optimal application rates and methods. This knowledge is essential for the development of effective fertilisation and management strategies for sustainable agricultural production, which will provide maximum benefits for soils, plants, the environment and the economy.

4.6. FERTILISERS FOR SUSTAINABLE AGRICULTURAL PRODUCTION

Lignite-based fertilisers have been shown to be a valuable component of sustainable agricultural practices, offering a range of benefits supported by scientific evidence (Maciejewska et al. 2024). Research indicates that lignite can serve as a suitable material for formulating slow-release nitrogen fertilisers, effectively reducing NH_3- volatilization, NO_3-leaching, and N_2O -emission compared to conventional urea fertilisers (Chen et al. 2023). Additionally, biochar, another organic amendment derived from pyrolyzing biomass, has been found to improve soil fertility and quality, enhancing phosphorus availability and crop productivity when integrated with organic and mineral phosphorus fertilisers (Rashid et al. 2023). Furthermore, the production of liquid fertilisers from waste materials, such as digestate from the fermentation process, contributes to a circular economy approach, reducing the energy intensity of the fertilizer industry and promoting the reuse of valuable plant nutrients from organic waste (Bassey, Oko 2023). These findings collectively support the notion that lignite fertilisers play a crucial role in sustainable agriculture by providing a natural and environmentally friendly alternative to conventional mineral fertilisers, contributing to waste recycling, and minimizing negative environmental impacts.

Lignite fertilisers are characterised by their ability to improve soil structure, increase water retention and provide nutrients in a form that is easily absorbed by plants. The long-lasting release of nutrients from these fertilisers contributes to a long-lasting and even supply of nutrients to plants, which has a positive effect on their growth, development and yield.

In sustainable agricultural production, fertilisers play a key role in enabling efficient and ecological use of soil resources and increasing agricultural yields. Fertilisers are used to provide plants with essential nutrients, such as nitrogen (N), phosphorus (P), potassium (K) and micronutrients, which are necessary for their growth, development, crop formation and resistance to disease and environmental stresses.

In sustainable agricultural production, it is important to use fertilisers rationally and efficiently, minimising nutrient losses to the environment. There are many techniques and practices that enable the sustainable use of fertilisers, provided that the following recommendations are followed:

Performance of soil analyses: Before applying fertilisers, it is a good idea to carry out soil analyses to understand the chemical composition of soils and to determine the nutrient needs of plants. Based on the results of such analyses, fertiliser doses can be adjusted to provide plants with the right amount of nutrients.

Use of varied fertilisation: It is important to adapt fertiliser doses to the specific requirements of different crops and their development phases. Diversified fertilisation ensures the efficient use of fertilisers, minimising waste and environmental pollution.

Application of controlled-release fertilisers: Controlled-release fertilisers are designed to gradually release nutrients as plants need them. In this way, they prevent the over-application of fertilisers, thereby reducing waste and the environmental impact.

Use of organic fertilisers: Organic fertilisers, such as compost, manure or plant residues, are a valuable source of nutrients for plants. The use of organic fertilisers helps to maintain soil fertility, improves soil structure, increases water retention and provides organic matter, which is important for soil microbial activity.

Use of precision fertilisation technology: Precision fertilisation technologies, such as the use of variable yield mapping-based dosing or the use of sensors to assess plant health, allow fertiliser doses to be adjusted to the actual needs of plants in a given area, preventing over-application and reducing losses.

The sustainable use of fertilisers in agricultural production is crucial for minimizing negative environmental impacts and enhancing overall ecosystem health. Research indicates that enhanced efficiency fertilisers (EEFs) can improve crop yield, soil fertility, and nutrient use efficiency while reducing nitrogen leaching, greenhouse gas emissions, and air pollutants (Chen et al. 2023). Additionally, combining fertilisation techniques can significantly reduce mineral fertiliser application while maintaining crop yields and promoting organic carbon and total nitrogen storage in the soil (Zaragüeta et al. 2023). It is essential to address nutrient imbalances and optimize the use of nitrogen, phosphorus, and potassium fertilisers to ensure food security and environmental preservation (Penuelas et al. 2023). Moreover, the sustainable management of fertilisers is critical in mitigating the depletion of phosphate rock mines and improving phosphorus use efficiency to prevent environmental issues like water eutrophication (Babcock-Jackson et al. 2023). By implementing rational fertiliser management practices, agricultural producers can achieve high yields, protect water quality, and maintain a healthy environment for plants, animals, and humans, thus ensuring sustainable soil use and ecological balance.

Practical tips for the use of lignite fertilisers in sustainable agricultural production include correct dosage according to plant needs and consideration of local soil and climatic conditions (Maciejewska et al. 2024). It is also important to monitor soil composition and adjust fertiliser application rates to maintain an optimal nutrient balance. In addition, it is useful to take into account the principles of crop rotation and plant diversity, which helps to increase biodiversity and protect the soil from erosion and degradation.

The benefits of using lignite-based fertilisers in sustainable agricultural production are multifaceted. They offer a promising solution for sustainable agricultural production (Maciejewska et al. 2024). These fertilizers efficiently utilize natural resources, reducing the risk of over-application of mineral fertilizers and subsequent groundwater contamination. Additionally, lignite-based fertilisers enhance soil fertility, positively impacting crop quality and quantity (Chen et al. 2023). Furthermore, the use of lignite fertilizers helps decrease greenhouse gas emissions, contributing to the mitigation of climate change effects (Bassey, Oko 2023). The multifaceted benefits of lignite fertilizers, as supported by scientific evidence, highlight their potential in promoting sustainable agriculture by improving resource efficiency, soil health, and environmental sustainability.

To summarise the considerations for the use of lignite fertiliser blends, it should be stated that in sustainable agricultural production, the appropriate use of lignite fertilisers is one of the key elements that can contribute to economic efficiency, environmental protection and sustainable agricultural development. The research conclusions and practical tips for using lignite blends are important for farmers and gardeners who want to optimise the productivity and health of their crops. Nutrient availability in soils can be controlled more easily through the rational use of this fertiliser, resulting in healthier plants, greater and higher-quality crops.

EFFECTS OF USING LIGNITE IN FIELD CROPS

Initial attempts to use lignite for as a fertiliser were made during the inter-war period. At that time, lignite dust was mainly applied at 1.4-40 t/ha, resulting in a marked increase in wheat, potato and sugar beet yields. This increase in yields was explained by an improvement in the physico-chemical properties of the soil, especially in its structure and heat balance, and by the presence of micronutrients in the lignite (Kissel 1931; Fuchs et al. 1933).

In Poland, research into the agricultural use of lignite was carried out in the interwar period by Musierowicz (1938). Based on this research, the author concluded that lignite is important for improving the physical properties of light soils.

During the post-war period, work on the agricultural use of lignite was carried out in Poland under the direction of Lityński (1952). The positive effect of lignite as a fertiliser was mainly obtained on light sandy soils. Jurkowska's (1962) studies show that lignite increase the uptake of nitrogen, phosphorus and potassium from soils and greatly influences the stabilisation of the reaction. According to the author, lignite attenuates toxic concentrations of both mineral and organic substances thanks to its buffering properties. Yield increases on the light soil were also achieved by Reimann (1963,1969) using raw lignite at 5% by weight of soil. The author highlights the potential of using lignite to improve the soil sorption properties. According to the author, the sorption capacity of lignite is high and corresponds to that of well-decomposed low peats.

Research on lignite's fertilizing properties has a long history, with early recognition dating back to the eighteenth century. However, in the inter-war period, significant advancements were made in exploring and understanding lignite's potential as a soil enhancer and fertilizer. Studies have shown that lignite can be effectively utilized in various forms to improve soil quality and enhance plant growth. For instance, lignite has been successfully used as a carrier for slow-release nitrogen fertilizers, demonstrating its ability to reduce nitrogen losses significantly (Rashid et al. 2023). Additionally, lignin, a component of lignite, has been identified as a valuable material for slow-release fertilizer coatings, highlighting its potential in sustainable agriculture practices (Chen et al. 2020). Furthermore, research has indicated that lignite amendments in livestock manure composting can mitigate ammonia emissions and improve the quality of the final compost, showcasing lignite's multifaceted benefits in agricultural applications (Abhiram et al. 2022). This research looks at the effect of the amount and degree of lignite grinding on yield depending on the type of soil and crop grown. The yield increases achieved have been explained in various ways, most commonly by an improvement in the physical properties and structure of soils, the effect of organic lignite and an improvement in air-water relations. Of particular importance are humic acids, which are released during the decomposition of lignite, improving soil structure and enriching the soil with humus compounds. Lignite has a positive effect on the heat balance of soils, reducing diurnal temperature fluctuations, while excessive grinding, i.e. the use of large quantities of coal fines, reduces water circulation in soils, thereby improving soil moisture.

The use of lignite for fertiliser purposes in its unmodified form is the simplest treatment, requiring no preliminary preparatory steps. For this purpose, both waste coal, commonly referred to as middlings, and coal that has been pre-crushed to a grain diameter fraction of less than 8 mm can be used. Carbon doses can vary depending on the granulometric composition and, in extreme cases, can be a stand-alone substrate in plant cultivation.

Unmodified lignite is a good fertiliser, improving the quality of both light and heavy soils. For light soils, it significantly increases the nutrient sorption and water retention capacity and provides humus compounds. Conversely, in the case of heavy soils, it increases their permeability. It was found that the application of lignite crushed to a grain diameter of less than 2 mm at a rate of 1×10^4 kg/ha to very light soils increased their water retention capacity by around 20%, while fertilising heavy soils with lignite of a grain size of 2-4 mm increased their permeability considerably and improved their structure.

5.1. CHANGES IN SOIL PROPERTIES AS A RESULT OF VARYING LIGNITE APPLICATION RATES

Research has extensively explored the impact of carbon on soil properties, particularly focusing on biochar and lignite. Studies have shown that biochar amendments can lead to a positive priming effect, with different types of biochar affecting soil organic carbon mineralization differently (Zhang et al. 2022). Additionally, biochar has been found to have high carbon sequestration potential and can improve agrochemical parameters in soil over time (Kocsis et al. 2018). Furthermore, Actosol application has been shown to enhance soil properties, increase nutrient availability, and improve maize yields, indicating the positive impact of carbon-rich substances on soil quality and productivity (Solek-Podwika et al. 2023). Moreover, biochar has been demonstrated to alter soil and pore water properties, reducing the bioavailability of contaminants like cadmium and promoting plant growth (Su et al. 2021). Some studies have focused on the sorption of lignite in soil samples in relation to fineness, moisture content and other characteristics (Augustyn 1984), finding that lignite exhibits ion-exchange properties that are beneficial when using this raw material not only as a substrate in plant cultivation, but also as an ameliorative soil additive. Lastly, research on post-mining soils has highlighted the potential for carbon sequestration, with different remediation techniques influencing the stability and composition of sequestered carbon (Kowalska et al. 2021).

However, the effects of using lignite in field crops depend on the following factors:

- the origin of the lignite,
- the degree of its fragmentation,
- dose size,
- physical and chemical properties of the soil,
- climatic conditions,
- crop species.

Crushed lignite is most effective on sandy soils with low sorption capacity, on highly acidic soils and on soils containing toxic components. A key advantage of using lignite in field crops is its slow mineralisation, which results in a lasting improvement in the physico-chemical properties of the soil, important for its agricultural value.

In order to illustrate the effects of the organic matter contained in lignite on the improvement of soil properties, let us first analyse the results obtained from the many years of research conducted by Maciejewska (1994).

The aim of this research was to evaluate the possibility of increasing the organic matter content of a sandy soil by means of an organic-mineral fertiliser made from brown coal and peat, enriched in macro and micro nutrients.

Meeting this objective meant:

- carrying out tests on the effects of organic-mineral fertiliser on soil properties,
- determining the properties and mineralisation rate of organic matter introduced into soils with organic-mineral fertiliser.

The scope of the research undertaken included the selection of suitable material for sustainable soil fertility improvement. Therefore, the first stage of the study analysed the results to date of the agricultural use of organic matter of various origins, e.g. raw lignite, lignite ash and dust, and waste organic-mineral preparations. Based on this analysis, it was concluded that the most favourable substance for this purpose was an organic-mineral substance made from brown coal and peat, supplemented with the macro- and micro-nutrients necessary for proper plant development.

The next stage of this work was the experimental verification of the agricultural suitability of the fertiliser proposed for the study. The extensive literature on the use of lignite for fertiliser purposes, as well as numerous papers on pot experiments and rigorous experiments, encouraged large-scale research. It was therefore decided that this topic would be addressed by conducting a field experiment.

As a natural product of the experimental stage, the effect of the organic-mineral fertiliser made from lignite on soil properties was assessed on the basis of results from five years of field experiments.

This assessment was based on a study of the effects of this fertiliser on changes in the soils: physico-chemical, chemical, physical and water properties.

The properties of the organic matter contained in this fertiliser and its humification rate were also studied, as well as the fertiliser's effect on plant development and yield.

The organic-mineral fertiliser made from lignite and peat, the m main focus of the study, has the character of a reclamation fertiliser. It is designed for the one-time enrichment of weak sandy and chemically degraded soils with organic matter, plant nutrients such as calcium, magnesium and potassium and micronutrients essential for plant development.

The organic matter contained in the tested fertiliser represents approximately 80% of the total air-dry mass of the fertiliser. It consists of lignite and peat in a ratio of 5 by weight: 1. Lignite was used in crushed form with a particle diameter of less than 1 mm.

Peat was introduced into the fertiliser mainly as a component to improve the water properties of the soil. Peat shows a high water retention capacity, while it has little fertilising value. Research shows that 1 dm^3 of high peat retains 0.9 litres of water (Maciejewska 1994).

The third key component of the fertiliser is the lignite ash from the second and third zones of the electrostatic precipitators. It is added to fill empty soil voids. Lignite ash is also a source of calcium, magnesium and trace elements.

In its most basic version, one tonne of the tested fertilizer contains around 800 kg of air-dry lignite and peat, about 130 kg of lignite ash, 10 kg of $Ca(NO_3)_2$ as a nitrogen source, 70 kg of $Ca(H_2PO_4)_2 \cdot H_2O$, 5 kg of a high-potassium salt, and 0.1 kg of $CuSO_4 \cdot 5H_2O$. All other components, such as magnesium, iron and trace elements, are derived exclusively from lignite and ash.

The composition of the fertiliser used in the experiments is shown in Table 15.

Table 15. Composition of organic-calcium mineral fertilizer.

Component mass	[kg]
Organic matter (80% lignite, 20% peat)	786
Lignite ash	130
Single superphosphate	70
Calcium nitrate	9
Potassium salt	5
Total	1000

Source: based on Maciejewska (1994).

A key advantage of organic-mineral fertiliser is its high content of slowly mineralising organic matter and the possibility of adapting its composition to the needs of the soil being reclaimed.

The soils selected for the study were rustic soils formed from loose sands, belonging to the VI quality class. Up to a depth of 100 cm, these soils are dominated by a predominantly fine sand fraction, with a very low content of dust fraction and flowable parts. These are acidic soils with a low degree (up to 20%) of saturation of the sorption complex with alkalis, characterised by low humus content (%Corg - 0.70%).

Organic-mineral fertiliser made from lignite was introduced into the soils at a particular time at the following rates: O (control field), 40, 80, 160 t/ha and ploughed with seed. The study was conducted over a period of five years (Maciejewska 1994).

Lignite fertiliser **has had a positive impact on changes in soil properties**. A clear improvement was found, mainly in soil pH. Following the application of a fertiliser at a rate of 160 t/ha, the soil $pH_{(H2O)}$ values increased by almost two units in the first year, reaching a neutral reaction, and remained at this level throughout the study period, i.e. 5 years.

The applied fertiliser **caused a significant decrease in potential acidity**, as shown by the pH values of the soil samples in the 1 M KCl solution. The changes in potential acidity show that the sorption complex of sandy soils, which is generally saturated with aluminium and hydrogen ions, was saturated with basic ions after the application of the fertiliser under study. Such significant changes in soil pH are believed to be caused by the presence of calcium contained in the lignite ash of one of the components of this fertiliser. Furthermore, organic matter is known to immobilise aluminium compounds, further mitigating the acidification of soils resulting from the presence of aluminium (Maciejewska 1994).

The applied fertiliser **improved the sorption properties of the tested soils**. This is can be seen in the higher sum of exchangeable cations in the organic-humus horizons. Following fertiliser application, there was a clear increase in the sorption capacity of the soils studied and an increase in the degree of base saturation of their sorption complex. The sorption capacity of soils fertilised with a dose of 160 t of fertiliser/ha increased more than four-fold, and the degree of base saturation was more than 90% (Maciejewska 1994).

Organic-mineral fertiliser in the tested soils **resulted in a three-fold increase in total organic carbon content**. It is worth noting that a comparable increase in organic carbon content was obtained at the Experimental Plant in Skierniewice following the yearly application of extremely high doses of manure (60 t/ha/year) over a 55-year period (Myśkow 1982). It should be emphasised that the achieved three-fold increase in organic carbon content following a single application of the tested fertiliser practically persisted throughout the study period. This means that mineralisation of the organic matter introduced with fertiliser occurs very slowly. This is particularly important in sandy and degraded soils, where the organic matter content is inherently low. It should also be noted that organic matter is prone to mineralisation in this type of soil.

The improvement in the sorption properties of the soils is explained by the presence of lignite, which has a sorption capacity of 1000 $cmol^+/kg$ in relation to base cations. Lignite therefore acts as a natural sorbent, which, in a soil-plant-fertiliser system, can sorb mineral fertiliser components or provide a source of certain nutrients.

The **total nitrogen content of** the ornamental horizons of the soils studied also increased as a result of fertiliser application.

The applied fertiliser **increased the content of bioavailable forms of nutrients** in the tested soils. This is particularly true of magnesium and calcium. There was a slightly smaller increase in phosphorus content due to the rather low content of this element in the lignite.

There are believed to be two factors that resulted in the increase in nutrient content. The tested fertiliser provides an additional source of these nutrients on the one hand, while the improved sorption properties of the soils make it possible to bind the fertiliser nutrients introduced during systematic mineral fertilisation on the other, significantly reducing their leaching into the soils.

The lignite fertiliser had a **positive impact on the physical and water-related properties of** the organic-humus of the soils studied (Maciejewska 1994).

The changes in these properties depended on the amount of fertiliser applied and were greatest after the introduction of 160 t of fertiliser/ha into the soils. The density of soil with an intact structure and dried at 105°C also decreased.

The applied fertiliser caused an increase in the total porosity of the tested soils and **a more than two-fold decrease in their air capacity**. In these soils, the proportion of capillary pores had changed. The direction of change shows that the number of capillary pores occupied by water had increased relative to the number of pores occupied by air. This significantly improved the water management of the soils studied. Once the tested fertiliser had been applied, the ornamental levels of the soils showed a higher water-holding capacity compared to the control sites of both experiments. A study by Maciejewska (1994) shows that the amount of water retained by 1 dm^3 of soil from the control field was 500 cm^3, while 1 dm^3 of soil fertilised with 160 t of fertiliser/ha retained 630 cm^3 of water. Accordingly, the ornamental horizons of the soils fertilised with lignite fertiliser showed higher moisture content. This is reflected in the two-fold increase in the moisture content of the soils at the time of collection and the approximately 79% increase in field water capacity compared to the control fields. The hygroscopic water content and capillary water capacity also increased. The above results confirmed the findings of the initial study (Maciejewska 1993b).

The effect of time on the changes in the soil properties analysed, which were obtained after a single application of the tested fertiliser, is described by regression equations, the most indicative of which are shown in Figure 21.

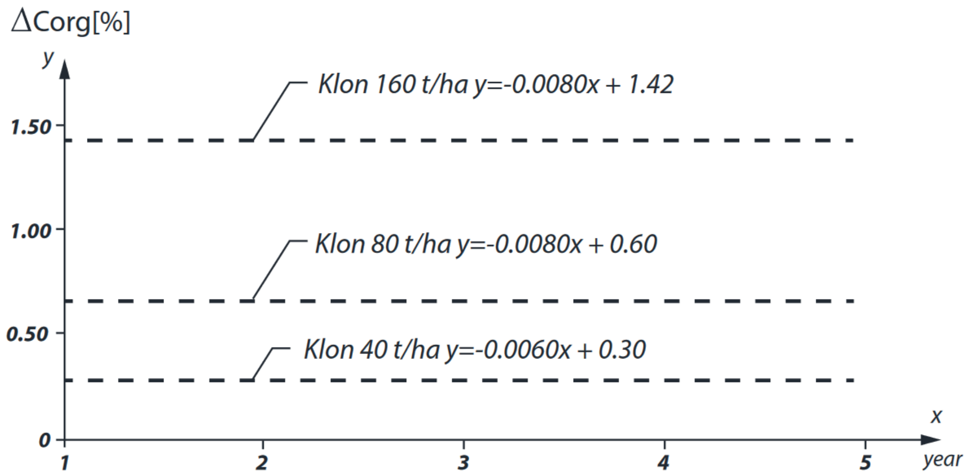

Figure 21. Time dependence of changes in Corg (OC) content [%] over time.

Source: own elaboration.

The organic carbon content changed only slightly over five years in both experiments. The regression equations show that after the application of 40 t/ha of the tested fertiliser, the decrease in organic carbon was 0.02%, and 0.03% at 80 t/ha.

The following conclusions can be drawn from the research carried out:

The resulting lignite fertiliser, with the addition of peat and lignite ash, improved the properties of the soils as follows:

1. change in the pH of the soils within the range of 1-2 pH units, resulting in a decrease in active and potential acidity in the organic-humus horizons of the soils,
2. average increase of 0.81% to 2.21% in the total organic carbon content, and an improvement in the sorption properties of the soils, reflected in the increased sum of base cations and the saturation of the sorption complex with alkalis.
3. improvement of the air-water properties of the organic-humus horizons of the soils in which it was found:

- lower density of the solid phase; lower density of the soil with the structure intact and 105% dried;
- lower air volume;
- improved ability of soils to retain rainwater, as shown by a more than two-fold increase in soil moisture and around a 1.5-fold increase in field water capacity.

5.2 PLANT YIELDS

Observations of plant growth and development were also made during the five-year study. Based on these observations, there was a clear plant response to the amount of fertiliser received from the lignite. Plant development was most intensive in fields fertilised at 160 t/ha. The plants were characterised by an intense green colour and a strongly developed root system. No leaf yellowing was observed among these plants.

Plants grown in a field fertilised at 80 t/ha looked only slightly weaker than previously discussed. Among these plants, yellowed leaves were found very occasionally and mainly in their lower parts. The strong green colour of the remaining leaves was evidence of the positive impact of the fertiliser applied. The root system of these plants was also well developed and strong compared to the plants in the control field, as shown in Figures 22–23.

Figure 22. Potato plant growth and root development in response to increasing Rekulter fertilizer doses (0, 40, and 160 t/ha). Source: own elaboration.

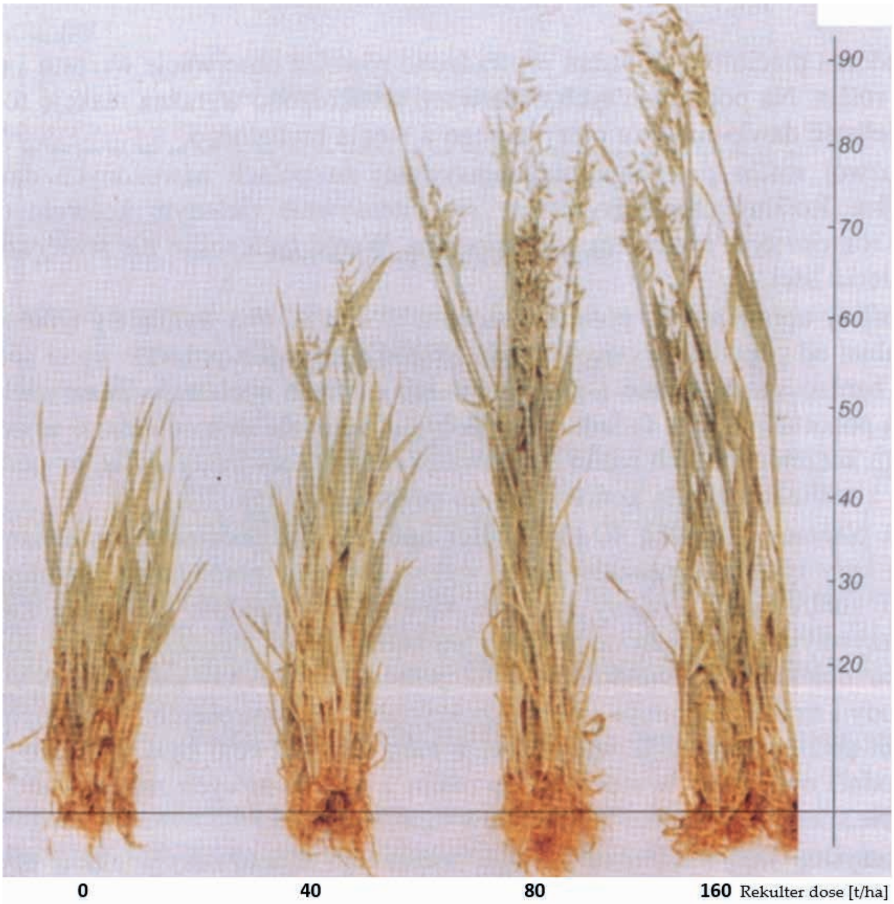

Figure 23. Oat plant growth and root development in response to increasing Rekulter fertilizer doses (0, 40, 80, and 160 t/ha). Source: own elaboration.

In the plantation with a dose of 40 t/ha, the above- and below-ground parts of the cultivated plants were only slightly better developed compared to the plants in the control field. The plants in the control field differed significantly in their unfavourable appearance from those in the other fields. Poor emergence and lower plant densities in the control field coverages were observed during the course of the study at both experimental sites. Plant development was also uneven. In most of them, the development stage was significantly (about 2 weeks) delayed compared to plants from fields where fertilisation had been applied.

The positive impact of the lignite fertiliser recorded during the one-year observations became apparent in the increase in yields. The higher the fertilisation application rate, the greater the yields of all crops grown, as shown in Table 16.

Table 16. Effect of mineral-organic fertilizer on crop yield (dt/ha).

Plants	Experiment in Niegowo				Experiment in Klon			
	fertiliser rates [t/ha].							
	0	40	80	160	0	40	80	160
Potatoes	53	130	160	196		—	—	
Oats	14	16	20	29	8	15	19	22
Rye	25	29	32	44	n	15	20	29
Rye	23	27	31	40	—	—	—	—
Total yield in cereal units	77	109	131	174	19	30	39	51
Average yield per year	15.4	21.8	26.2	34.8	9.5	15	19.5	25.5
Relatively	100	142	170	226	100	158	205	268

Source: based on Maciejewska (1994).

Fertilisation with lignite also leads to an increase in the protein content of the grain while reducing its content in straw. Meanwhile, an increase in protein and starch content results in a decrease in ash content, a trend observed in both grain and straw. Lignite affects the formation of grain that is poorer in ash, which is the result not so much of a poorer uptake of mineral nutrients, but of the production of a more plump grain and the appropriate distribution of these nutrients between grain and straw (Lityński et al. 1952).

The positive impacts of lignite fertiliser and lignite ash have also been reported in vegetable cultivation (Suchorska-Orłowska 1998). The author's research shows that the applied fertiliser had a positive impact on the yields of onion, beetroot, head cabbage, carrot and spinach. The yields obtained were comparable to those from the manured facilities.

According to Maciejewska (1994), fertiliser obtained from lignite dust and lignite ash can be successfully used as a substitute for manure to fertilise vegetable plants, as it not only increases yields, but also improves their quality.

5.3. EFFECT OF ORGANIC MATTER FROM LIGNITE IN BLOCKING HEAVY METALS IN SOILS

Intensive industrial activities without adequate environmental safeguards result in elevated concentrations of heavy metals in soils, as evidenced by studies in China and Xuzhou City (Ma et al. 2023; Yang et al. 2023). This accumulation of heavy metals, such as Cd, Pb, and As, not only disrupts plant vegetation but also poses significant health risks to consumers, especially children, through the trophic chain (Yang, Yang 2023; Velayatzadeh 2023). The presence of heavy metals above pollution thresholds in soils can lead to irreversible changes, forming biologically inactive formations and impacting the ecological balance, as highlighted in research on heavy metal pollution in agricultural soil in Hubei Province, China (Su et al. 2023). These findings underscore the critical importance of effective environmental management to prevent the over-accumulation of heavy metals and mitigate the associated risks to both ecosystems and human health.

The extent to which the soil retains heavy metals is determined by its sorption capacity, which depends on the quantity and quality of the colloids that make up the soil sorption complex. The basic component of this complex is humus compounds, which play an important protective role against heavy metal contamination of water and plants.

Humic acids, especially humic and fulvic acids, have free negative charges that form on the functional groups R-COOH, R-OH, and R-NH_2. However, carboxyl groups have the greatest role in the formation of these charges (Hofstede, Ho 1991). The number of functional groups also depends on the molecular weight of the acid; the lower the weight, the higher the amount of functional groups per unit weight. The formation of free uncompensated charges on the functional groups of humic acids increases significantly at higher soil pH values. Under such conditions, OH^- ions appear in the soil solution which can deprotonate the functional groups, releasing a free, uncompensated negative charge according to the reactions:

$$R\text{-}COOH + OH^- \rightarrow R\text{-}COO^- + H_2O$$

$$R\text{-}OH + OH^- \rightarrow R\text{-}O^- + H_2O$$

The functional groups of humic acids can combine with monovalent, divalent or trivalent metals. Organic-mineral complexes with metals of two or more values are most often called chelates. These acids have a chain structure, and then chain chelates or ring chelates are formed, creating ring chelates.

The formation and persistence of chalcane complexes in the soil depends on a number of factors, most notably the amount and structure of humic compounds, soil pH and type and concentration of metal in the soil. However, the prevailing opinion is that humus has the greatest influence in reducing the solubility and availability of heavy metals to plants. The strength of the bond between a metal and an organic substance is not the same for individual heavy metals. Mocek and Owczarzak (1993) obtained the following amounts of metal bound to organic matter in relation to the total content of these metals in soils: Cu 45-60%, Pb 38-57% and Zn 12-24%. The formation and persistence of chelate bonds also depends on the type and molecular weight of the humic acids. Steinbrich and Turski (1986) report that during the breakdown of high molecular weight soluble complexes (about 150,000), low molecular-weight and less soluble complexes are formed. The higher the humus content in soils, the less soluble the heavy metal chelates formed. While investigating the leaching of some heavy metals in the columns, Weber (1993) obtained lower displacement of these metals with higher humus content.

The formation and persistence of chelates is influenced by the soil pH. As soil pH increases, so does chelate persistence (Hofstede, Ho 1991; Bar-Tal et al. 1988; Chairidchai, Ritchie 1992; Stahl and Bruce 1991). There are many reasons for this: At low pH values, humic acid molecules are assembled into colloid aggregates with very few free, uncomplexed negative charges (Hofstede, Ho 1991). At higher pH values, metal hydroxides are formed (e.g. $Zn(OH)_2$ instead of Zn^{2+} and humic acids can bind more metals. This is supported by studies showing that an increase in solution pH from 3.8 to 5.6 led to a sixty-fold increases in the concentration of Zn(OH) in solution (Chairidchai, Ritchie 1992).

The results of the study indicate that to reduce the uptake of heavy metals by plants, soil pH should be kept high and high doses of organic fertilisers should be applied, especially those that are slow to mineralise.

By analysing the role of organic matter in soils, the ability of humus fractions to form complex compounds with metals identified. This observation led to the proposal and development of the thesis that the organic matter of lignite could be used for this purpose. The findings of Augustyn (1984) confirm the validity of the thesis that lignite from the *Kazimierz* open pit, KWB *Konin*, is highly capable of sorbing heavy metal cations, such as copper, manganese and chromium. Similar observations in relation to soil humus, peat and brown coal are found in the works of Mercik and Kubik (1995) and Maciejewska et al. (1995).

A. Maciejewska conducted research on the use of an organic-vineral fertiliser made from the lignite Rekulter from 1985. The results obtained led to the extension of such research, which later incorporated the impact of this fertiliser on reducing the uptake of heavy metals by different plant species. The results also suggested that the organic matter in the fertiliser increases the buffering capacity of soils.

This thesis was based on an analysis from previous studies, which shows that the stability of organic matter-metal bonds depends, among other things, on the activity of humus acids. The chelating properties of these acids towards heavy metal cations can significantly reduce their availability to plants. Based on the results of tests on the sorption of certain heavy metals by lignite, it is highly likely that the tested fertiliser, Rekulter, also possesses this ability. **Therefore, studies were conducted with the aim of analysing the impact of various doses of Rekulter on the amount of heavy metals taken up from soils by different species of plants cultivated on soils burdened with these metals (Maciejewska 1998).**

The proposed experimental design and the range of chemical analyses made it possible to determine the extent to which heavy metals in soils are bound by the organic matter contained in the tested fertiliser.

Three soil types were used in the experiments, which were taken from the strict field experiments of the SGGW Experimental Field. The soils used for the experiments are characterised by different reaction and heavy metal cation content.

1. Acidic soil with pH = 4.9, contaminated with heavy metals that have been introduced into the soils in the form of the following compounds: cadmium as $Cd(NO_3)_2$, lead as $Pb(CH_3COO)_2$, and zinc as $ZnSO_4$.
2. Soil limed with magnesium lime, containing no heavy metal cations. Magnesium lime was applied to these soils at a rate calculated according to 2Hh. The soil reaction was pH = 7.1.
3. Soil limed with lime from a lead smelter at a rate calculated by 2Hh, containing significant amounts of heavy metals. The pH of these soil was 6.6.

The study shows that the applied organic-mineral fertiliser Rekulter, derived from lignite, clearly influenced the heavy metal content of the crops. This effect was evident in both acidic and limed soils. The content of the analysed heavy metals in the plants was dependent on the amount of fertiliser applied and decreased as the dose increased.

The highest dose of fertiliser, 150 t/ha, reduced the uptake of

- **zinc** by 50% in serradella, triticale, maize and oilseed rape, and by 40% in spinach,
- **lead** by 50% in serradella, triticale and maize, and by 30% in spinach and oilseed rape,
- **cadmium** by 50% in maize and oilseed rape, by 40% in serradella and by 30% in spinach and triticale (Maciejewska 1998).

SUMMARY

Based on the literature cited and the research carried out, it can be concluded that both raw lignite and organic-mineral fertilisers made from lignite improve soil fertility. The impact of these fertilisers on soils is both direct and indirect. Their direct impact is explained by their chemical compositions, i.e. the content of fertilising elements, micronutrients, humic acids and their salts, while their indirect impact is attributed to the strongly developed porous system of lignite, with which the protective functions of this fertiliser are most closely associated.

The protective function of organic matter, introduced into soils with organic-mineral fertilisers, consists primarily in:

- weakening the effect of an acidic soil reaction by binding aluminium, manganese and iron compounds, mitigating the toxic effects of these metals,
- increasing the capacity of the sorption complex, and thus, increasing the resistance of soils to degradation,
- easing the reaction of humus substances with minerals, cations and other organic substances,
- improving the buffering properties of soils by reducing excessive concentrations of bioavailable forms of mineral nutrients and binding heavy metals,
- its positive impact on the physical and water properties of the soils, causing a decrease in air capacity and a marked increase in capillary water capacity.

The ecological properties of the introduced organic matter are particularly important with regard to soil nitrogen management. As is well known, nitrogen is a highly mobile element with a high transformation rate, hence the important of its fixation by organic matter and retention in soils.

Considering:

- the yield-forming value of organic matter from lignite,
- the protective effect of this substance against chemical degradation of soils,
- an abundant supply of both lignite and the various components necessary for the production of organic-mineral multi-nutrient fertilisers,
- the possibility of adapting the composition of the fertiliser to the needs of soils and plants,
- it should be concluded that organic-mineral fertilisers made from lignite should be widely used. They are primarily used on soils with a low humus content, those that are susceptible to degradation, degraded soils, and soilless land in need of reclamation.

Here are the key conclusions and value additions from each chapter:

Chapter 1: Soil - A Natural Planetary Resource

- Highlights the crucial role soil plays as a foundation for agriculture, biodiversity, and life on Earth.
- Examines how factors like bedrock, climate, topography, soil organisms, and human activities shape the diverse physical, chemical, and biological properties of soils globally.
- Underscores the importance of understanding soil formation processes, properties, and functions for soil conservation and sustainable management.

Chapter 2: Soil Organic Matter

- Reveals the vital functions of soil organic matter (SOM) in maintaining soil fertility, structure, water retention, nutrient cycling, and overall ecosystem health.
- Elucidates the ecological significance of humus, its formation process, effects on soil properties like structure, buffering capacity, metal/pesticide binding.
- Emphasizes the need for rational SOM management strategies to preserve soil quality and productivity.

Chapter 3: Characteristics of Brown Coal (Lignite)

- Identifies lignite as a valuable unconventional source of organic matter with unique chemical composition and sorption properties.
- Explores lignite's fertilizing value, presence of humic acids, ability to absorb pollutants and bind heavy metals.
- Highlights lignite's potential for soil amendment, remediation and environmental protection.

Chapter 4: Lignite Fertilizer Blends

- Examines various formulations like humic-mineral, nitrohumin-mineral, humin-micronutrient blends derived from lignite.
- Evaluates their efficacy in promoting soil fertility, nutrient availability and sustainable agricultural production.
- Provides insights into tailoring lignite-based fertilizers to specific soil and crop needs.

Chapter 5: Effects of Using Lignite in Field Crops

- Investigates the practical impacts of varying lignite application rates on soil properties and crop yields.

- Demonstrates lignite's ability to improve soil structure, water retention, nutrient availability.
- Reveals lignite's potential for heavy metal immobilization and soil remediation.

In summary, this comprehensive work advances our understanding of soil as a vital resource, the importance of SOM and humus, lignite's value as an organic amendment, formulations of lignite-based fertilizers, and their real-world applications in sustainable agriculture and environmental remediation.

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This book is a joint work authored by Alina Maciejewska, Łukasz Kuzak, Janusz Sobieraj, and Dominik Metelski. Each author brings a unique perspective and expertise that significantly contributes to the book's exploration of lignite as a natural source of organic matter and its implications for soil health.

ALINA MACIEJEWSKA - the principal author, is a distinguished professor in agricultural sciences with a focus on environmental protection and soil restoration. Her extensive background includes a PhD in soil science and a habilitation in environmental engineering. Professor Maciejewska's research emphasizes the restoration of organic matter in degraded soils, making her insights particularly relevant to the book's theme of enhancing soil fertility through organic-mineral fertilizers derived from lignite. Her involvement in projects aimed at producing organic-mineral fertilizers from lignite and studying its effects on heavy metal accumulation in crops highlights her commitment to sustainable agricultural practices and soil health improvement.

ŁUKASZ KUZAK - serves as a Research and Teaching Assistant at the Faculty of Geodesy and Cartography at the Warsaw University of Technology. His specialization in the revitalization of post-industrial areas and the application of spatial analysis in environmental sciences complements the book's objectives by providing a framework for understanding how lignite can be utilized in reclaiming degraded lands. Kuzak's expertise in identifying and assessing contaminated urban areas is crucial for discussing the practical applications of lignite-based fertilizers in agricultural systems, particularly in urbanized contexts.

JANUSZ SOBIERAJ - is an Assistant Professor in the Department of Building Engineering at the Warsaw University of Technology. He possesses extensive experience in executing revitalization and environmental projects, underpinned by numerous scientific publications. His expertise in construction management and applied economics allows him to contribute valuable insights into the economic aspects of using lignite as a fertilizer. Sobieraj's research on project management and environmental impacts is particularly relevant to the book, as it addresses the practical implications of integrating lignite-based fertilizers into agricultural systems, thereby enhancing soil health and sustainability.

DOMINIK METELSKI - a Research Assistant in the Department of Spanish and International Economics at the University of Granada (and member of the "AMIKO" research team /SEJ-609/), brings a multifaceted perspective to the book. In addition to his focus on economic topics, Metelski has authored numerous articles on sustainability, showcasing his interdisciplinary approach. His contributions to various research studies have resulted in publications in esteemed journals such as Buildings, Water, Energy, Applied Sciences, Toxins, and Land. This diverse body of work highlights his ability to connect economic theories with environmental practices, making his insights crucial for understanding the broader implications of lignite use in agriculture.

The knowledge presented in this book thus represents a synthesis of the authors' diverse expertise and rich experience, effectively bridging various fields to address the challenges of soil health and sustainable agricultural practices.

Lignite

a natural source of organic matter and its impact on soil health

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