UNIVERSITY OF DEBRECEN
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AND ENVIRONMENTAL MANAGEMENT
Institute of Food Science

WASTES AND BY-PRODUCTS AS POSSIBLE PLANT NUTRITION

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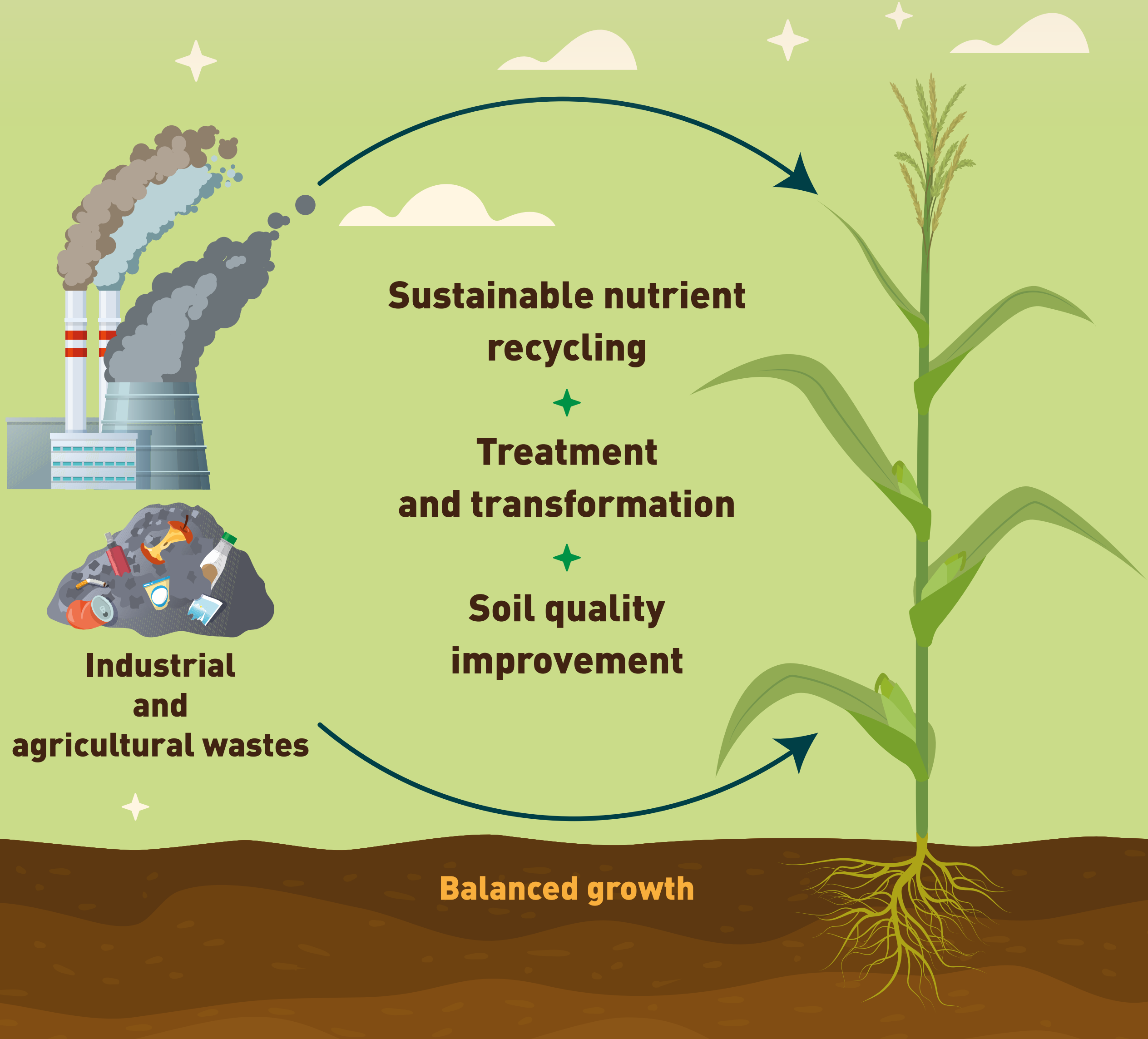

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1.
Introduction

Agriculture, the backbone of human civilization, is increasingly facing challenges due to soil degradation, nutrient depletion, and environmental concerns arising from the misuse of chemical fertilizers. To address these issues, a sustainable and environmentally conscious approach is imperative. One promising avenue is the utilization of industrial by-products and wastes as plant nutrients. This book explores the potential of these materials to enhance soil fertility, reduce waste, and foster sustainable agricultural practices.

Modern agriculture heavily depends on chemical fertilizers to meet the nutritional demands of crops. While effective in boosting yields, their excessive and prolonged use has led to detrimental environmental consequences, such as soil acidification, water pollution, and greenhouse gas emissions. Moreover, the limited availability of raw materials used in fertilizer production, such as phosphorus rock, highlights the urgency of finding alternative nutrient sources. Concurrently, industrial processes generate substantial quantities of organic and inorganic by-products, many of which are either underutilized or disposed of as waste, posing environmental hazards. Using these by-products as plant nutritional sources brings together waste management and sustainable agriculture.

Industrial by-products can replenish essential nutrients, reducing the dependency on synthetic fertilizers. Organic by-products enhance soil organic matter, improving water retention, aeration, and microbial activity. Inorganic by-products, on the other hand, provide a steady release of nutrients, ensuring sustained plant growth. Diverting industrial wastes from landfills or incineration to agricultural fields mitigates environmental pollution. This practice aligns with circular economy principles, promoting resource efficiency Utilizing industrial by-products can significantly reduce input costs for farmers, especially in regions where access to commercial fertilizers is limited. Industries also benefit by reducing disposal costs and compliance burdens.

Recycling wastes into agriculture reduces greenhouse gas emissions associated with waste disposal and fertilizer production. It also mitigates leaching and runoff, protecting water bodies from eutrophication. Despite its potential, the use of industrial by-products in agriculture faces several challenges. Many industrial wastes contain heavy metals, pathogens, or toxic compounds that pose risks to soil health, crop safety, and human health. To ensure these materials are used safely, rigorous treatment processes and strict quality standards are essential. This requires implementing strong regulatory frameworks and conducting thorough risk assessments. Technologies such as bio-remediation and thermal treatment can detoxify hazardous components in the industrial by-products. Farmers and consumers may be sceptical about using "waste" as a nutrient source due to concerns over safety and effectiveness. The collection, processing, and distribution of industrial by-products require infrastructure that may not exist in all regions.

As the world's human and animal population continue to grow, the demand for food and food production will rise, leading to increased waste generation and environmental challenges. In addition, more than two billion people worldwide are at risk of developing a micronutrient deficiency due to a lack of essential nutrients in their daily diet. The primary cause of this nutrient deficiency is that food crops often fail to supply adequate nutrients because they are grown in mineral-deficient soils. In most developing countries, agricultural production focuses primarily on increasing crop productivity and grain yield, often overlooking the challenges of malnutrition.

Environmental, human, animal, and climate health, as well as sustainable agricultural production and agro-industrial processing, heavily rely on efficient waste management. To achieve the goal of significantly reducing waste creation, reusing waste, and recycling trash, circular agricultural production and bio-economic agro-industrial waste management models are essential. The goal of transforming waste into valuable resources and establishing a zero-waste agricultural production system can be achieved through ongoing research and innovative thinking.

This textbook covers the classification of elements and their effects on plants, emphasising the physiological, biochemical, and antioxidant characteristics of plants. It also highlights the possible use of industrial and agricultural wastes and by-products in agricultural production, including case studies as well. This approach not only recycles nutrients, improves soil health, and reduces environmental pollution, but also supports global efforts to achieve sustainable development goals. However, its successful implementation will require collaboration among industries, policymakers, researchers, and farmers. If supported and successfully implemented, industrial by-products can transform from being an environmental liability to a valuable agricultural asset, paving the way for a greener and more resilient future.

2.
The effects and role of macro elements in industrial by-products and wastes

Plants require a range of essential nutrients to grow, reproduce, and carry out physiological processes vital for survival. These nutrients are divided into macronutrients and micronutrients based on the quantities required by the plant. Macronutrients – such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) – are needed in relatively large amounts in plants and play critical roles in various physiological and biochemical processes.

2.1. Nitrogen

Nitrogen is a cornerstone of life, serving as a critical nutrient for all plants. As one of the **essential macronutrients**, nitrogen plays a vital role in multiple physiological processes, including protein synthesis, energy transfer, and photosynthesis. Its significance extends beyond plant health, influencing agricultural productivity and ecological balance. Despite its abundance in the atmosphere, nitrogen's availability to plants is often limited due to its chemical inertness, requiring specific transformations before uptake.

Plants absorb nitrogen primarily in the form of nitrate (NO_3^-) and ammonium (NH_4^+) from the soil. However, achieving a balance between adequate nitrogen supply and environmental sustainability remains a key challenge in modern agriculture.

The **timing of N intake** was assessed in a number of studies. Research by Iowa State shows that at the silking stage (reproductive stage 1, R1), corn absorbs and stores about 60% (130 kg N/ha) of the total nitrogen needed for a high-yield crop of 15.13 t/ha. Total N uptake (stover + grain) was 22 kg N/ha by R6 (black layer). Using these statistics, additional computations show that in order to support grain development, 80 kg of N/ha must still be absorbed after blooming. The amount of N absorbed during and after flowering is documented in several recent papers. According to these findings, blooming absorbs roughly the same amount of nitrogen (an average of 63% and 62%, respectively) under low and normal N circumstances. The need for post-flowering N absorption still varies between 40 and 150 t N/ha, despite the fact that this represents a significant fraction of the total seasonal N.

Nitrogen exists in various forms in the biosphere, cycling between the atmosphere, soil, and living organisms. The nitrogen cycle ensures a continuous supply of this element to plants and other life forms (Figure 1).

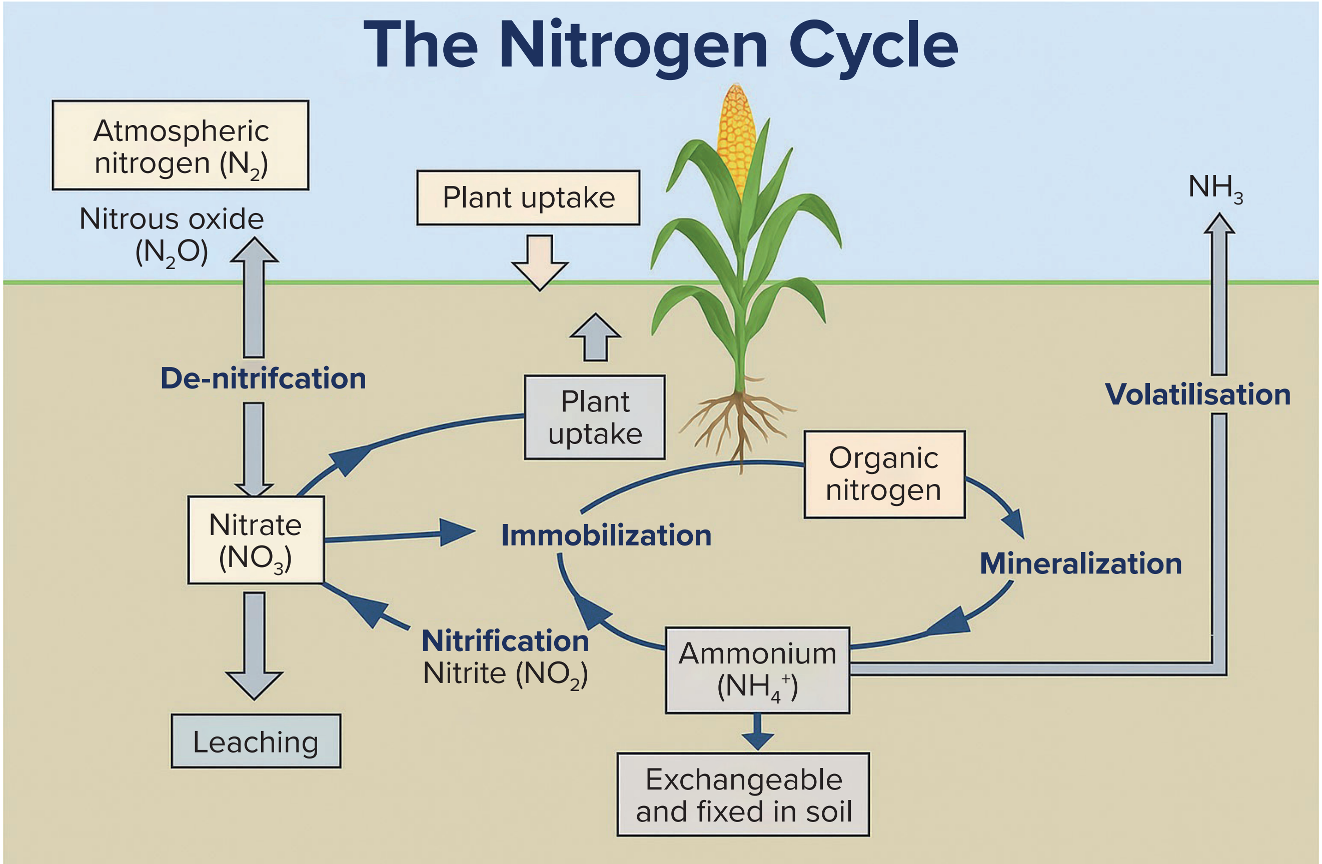

Figure 1: The Nitrogen Cycle: Nitrogen cycling through the various forms in soil determines the amount of nitrogen available for plants to uptake.
Source: Own editing

Atmospheric nitrogen (N_2) makes up approximately 78% of the air but is unavailable to most plants due to its stable triple bond. Nitrogen fixation converts N_2 into bioavailable forms. Symbiotic bacteria, such as *Rhizobium* and *Frankia*, convert atmospheric nitrogen into ammonium. Free-living bacteria like *Azotobacter* also contribute.

Industrial Fixation: The Haber-Bosch process synthesizes ammonia for fertilizers, revolutionizing agriculture but contributing to environmental concerns. Lightning and volcanic activity naturally convert atmospheric nitrogen into nitrates.

In the soil, nitrogen undergoes several transformations:

- ammonification: Organic nitrogen in decaying matter is converted into ammonium by microbes.
- nitrification: Ammonium is oxidized to nitrate by nitrifying bacteria like *Nitrosomonas* and *Nitrobacte*r.
- denitrification: Nitrate is reduced back to nitrogen gas by denitrifying bacteria, especially under anaerobic conditions.

Nitrogen is often lost from the soil through leaching, volatilization, and denitrification, posing a challenge for nutrient management. Leached nitrates contaminate groundwater, while gaseous nitrogen compounds contribute to atmospheric pollution. Nitrogen uptake by plants depends on its form in the soil and environmental conditions. Nitrate (NO_3^-) and ammonium (NH_4^+) are the primary forms absorbed, but each has distinct pathways and implications.

Nitrate, the most common form of nitrogen available in well-aerated soils, is absorbed by plant roots through nitrate transporters. Once inside the plant, nitrate can be stored in vacuoles for later use. Be reduced to nitrite (NO_2^-) in the cytoplasm by the enzyme nitrate reductase, followed by further reduction to ammonium in the chloroplasts by nitrite reductase.

This process requires energy in the form of ATP and reducing power (NADH or NADPH), making nitrate assimilation energy-intensive.

Ammonium, a less energy-demanding form of nitrogen, is absorbed through ammonium transporters. It is directly assimilated into amino acids via the glutamine synthetase-glutamate synthase (GS-GOGAT) pathway. However, ammonium in excess can become toxic, disrupting cellular pH and causing ion imbalances. Although most plants rely on inorganic nitrogen, some can utilize simple organic nitrogen forms like amino acids under specific conditions.

Soil pH, temperature, and microbial activity affect the availability and uptake efficiency of nitrogen. Acidic or waterlogged soils often reduce nitrogen availability.

Nitrogen is often lost from the soil through:

- **Leaching**: Nitrate, being highly soluble, can leach into groundwater, reducing soil fertility and contaminating water sources.
- **Volatilization**: Ammonia gas can escape into the atmosphere under high temperatures or alkaline conditions.
- **Denitrification**: Loss of nitrogen as N_2 or N_2O gases in waterlogged soils.

Understanding and managing these processes is essential for optimizing nitrogen availability while reducing environmental harm.

Some plants, particularly in nutrient-poor ecosystems, can absorb **organic nitrogen compounds**, such as amino acids, through specialized transport systems. This capability allows them to exploit alternative nitrogen sources.

Nitrogen is integral to several biochemical pathways, contributing to primary and secondary metabolism.

Nitrogen is a core component of amino acids, the building blocks of proteins. Proteins are essential for:

- Enzymatic catalysis of metabolic reactions.
- Structural support in cell walls and membranes.
- Transport of molecules, such as nitrate and sugars.

In addition, Nitrogen is a critical element in **chlorophyll**, the green pigment responsible for photosynthesis. Adequate nitrogen ensures efficient light capture and energy conversion, directly influencing plant productivity.

Nitrogen is also a fundamental part of nucleotides, the structural units of DNA and RNA. These molecules are vital for genetic information transfer, cell division, and metabolic regulation.

It contributes to the synthesis of alkaloids, phenolic compounds, and other secondary metabolites that enhance plant defense and adaptation to environmental stress.

Directly influences both vegetative and reproductive growth stages in plants.

It promotes the development of leaves, stems, and roots by enhancing cell division and elongation. Nitrogen-rich plants exhibit lush, green foliage due to increased chlorophyll synthesis.

It is also critical for flowering and seed production. It supports the formation of reproductive structures and ensures the development of viable seeds and fruits (Figure 2).

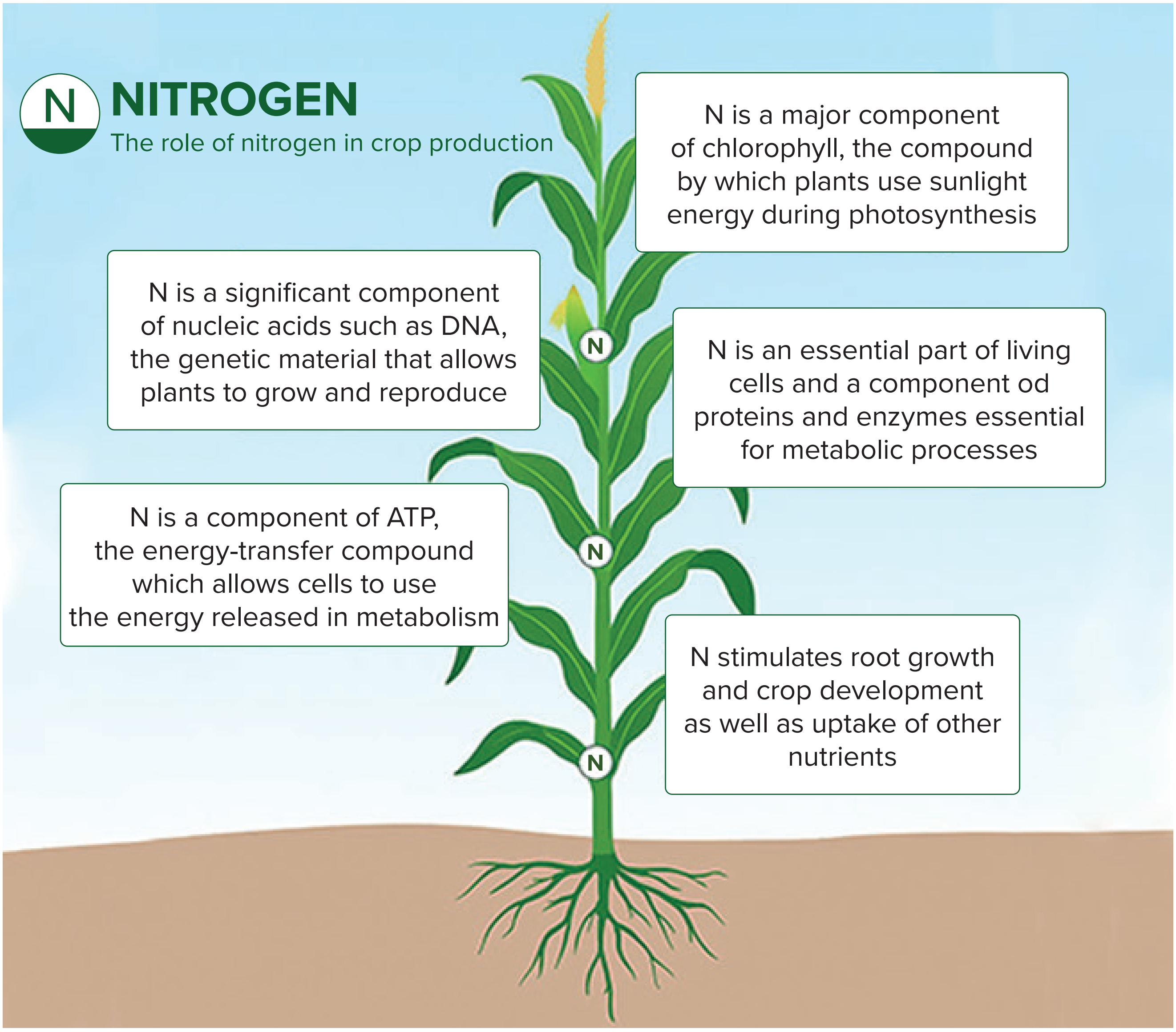

Figure 2: Role of nitrogen in plant production
Source: https://icl-growingsolutions.com/agriculture/categories/nitrogen-based-fertilizers/
Own editing

Nitrogen deficiency severely limits plant growth and productivity.

The term "**nitrogen deficiency**" describes a lack of nitrogen in plants. When high-carbon organic materials are added to the soil, it could happen. Sawdust is an example of this. Because nitrogen is absorbed by soil bacteria, plants are unable to obtain it, allowing them to continue breaking down carbon sources. Except for nitrogen-fixing legumes, practically every type of vegetable may be impacted by this practice, which is known as "robbing" the soil of its nitrogen content. Applying manure to plant leaves or mulching with grass clippings can prevent deficiencies from developing.

Nitrogen loss from the soil can be prevented by covering the soil with green manure crops, such as winter tares or grazing rye, during the winter. On the other hand, winter tares and other leguminous green manures will fix excess nitrogen from the atmosphere.

The following are the **main reasons why plants lack nitrogen**:

- In sandy, well-drained, rapidly leaching soils, N shortage is widespread.
- Plants that receive too much water from irrigation and rainfall experience a nitrogen shortage.
- In order to prevent nitrogen famine, proper soil aeration provides aerobic and facultative aerobic nitrogen-fixing bacteria with enough oxygen. In low-oxygen soils, however, denitrifying bacteria consume NO_2/NO_3. Plant-useful nitrates are also converted to the greenhouse gas N_2O by inadequate aeration.
- Temperature affects microbial activity and nutrient solubility, which releases nitrogen that plants can use. Crop nutrition is decreased by lower soil temperatures.
- Plants with high levels of potassium, magnesium, and zinc chlorides experience a nitrogen shortage.
- Soil salinity decreases the uptake of nitrogen because of osmotic pressure.
- The availability of agricultural nitrogen is impacted by pH levels.
- When pests or diseases infect damaged or impacted roots, they are unable to absorb nutrients as well. It eventually affects the uptake of nitrogen.
- Because it is easily washed away, high nitrogen solubility encourages nitrogen deficiencies in plants.
- Since organic matter is essential for nitrogen, low amounts indicate that the nitrogen is not well supplied to plants.

It should come as no surprise that the first signs of a plant insufficiency are frequently signs of ill health. The most common **symptoms** associated with insufficient nitrogen intake are listed below (Figure 3):

- The plant's higher leaves are a lighter shade of green, while the lower leaves are yellow (chlorosis).
- Branches or shoots that are not fully formed (stunted growth).
- Certain plant species may have purple patterns visible on their stems.
- As age progresses, the leaves will eventually wilt, become brown, and fall off.
- Flowering and fruit production will decline.
- Delay of plant growth.

- Decreasing the rate at which new leaves are produced.
- While the plant may produce more roots in an attempt to compensate for the lack of nitrogen, the shoot growth will be significantly stunted, leading to a higher root-to-shoot ratio
- Prolonged vegetative phase with poor reproductive growth (delayed maturity).
- Reduced protein synthesis, leading to poor enzymatic activity.
- Decreased photosynthetic efficiency due to low chlorophyll content.

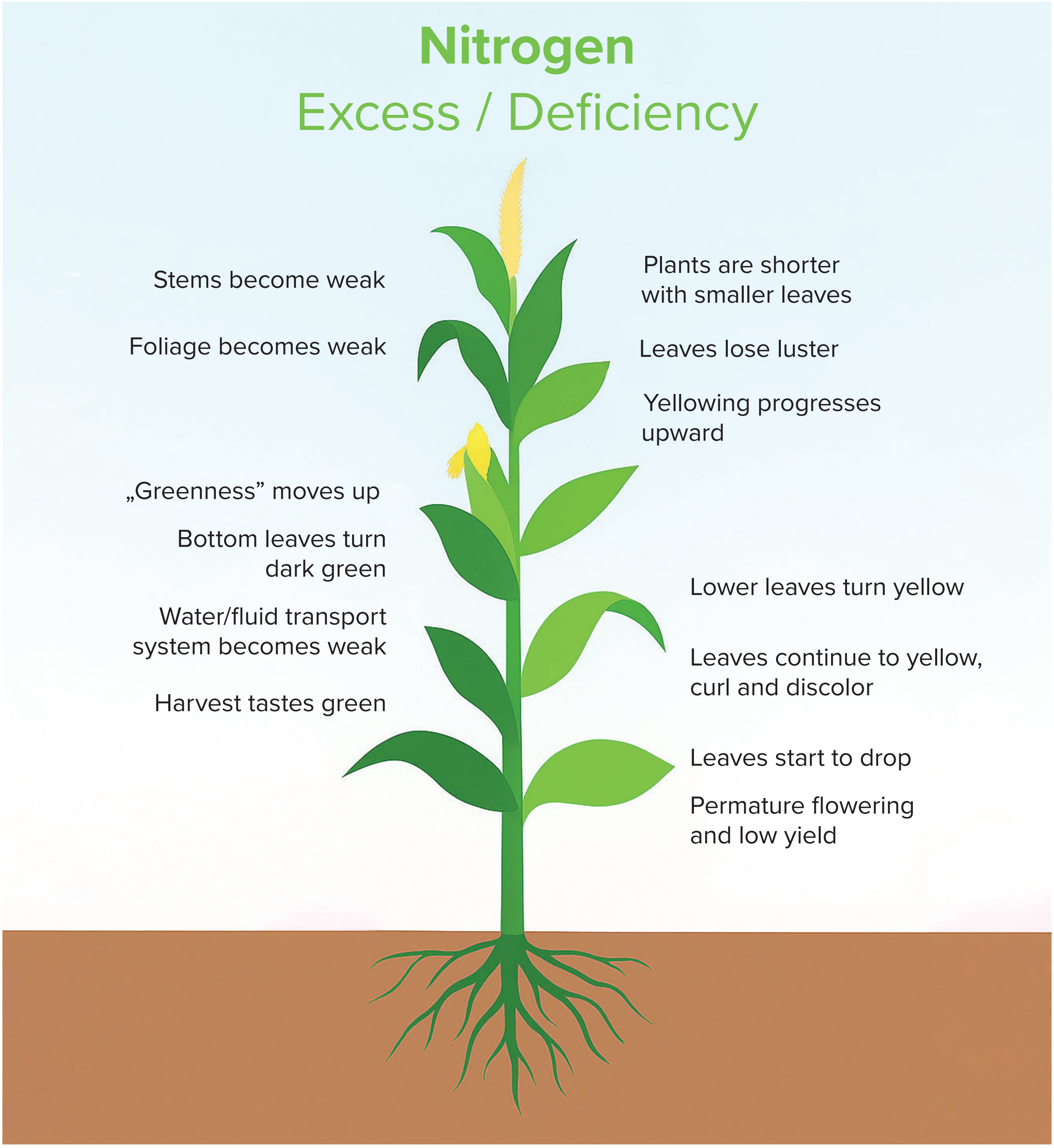

Figure 3: Effect of suitable and unsuitable nitrogen application on plants
Source: https://geopard.tech/blog/what-is-nitrogen-deficiency-and-how-to-fix-it-in-plants
Own editing

While nitrogen is essential, excessive application can harm plants and the environment. Over-fertilized plants may show excessive vegetative growth at the expense of reproductive development. Lodging, or the bending of stems, due to weak structural tissues. Leaching of nitrates into water bodies causes eutrophication, leading to algal blooms and aquatic ecosystem damage. Emission of nitrous oxide, a potent greenhouse gas, exacerbates climate change.

Nitrogen is indispensable for plant physiology, governing critical processes such as protein synthesis, photosynthesis, and growth. While essential, managing nitrogen effectively is a balancing act, requiring careful consideration of its benefits and potential environmental impacts. By adopting innovative strategies and sustainable practices, we can harness nitrogen's potential to ensure agricultural productivity and environmental stewardship for future generations.

2.2. Phosphorus

Phosphorus (P) is a fundamental macronutrient required for the growth and development of plants. Second only to nitrogen in importance, phosphorus plays an indispensable role in cellular processes that influence energy transfer, signal transduction, photosynthesis, and nucleic acid synthesis. Its deficiency can result in significant agricultural productivity losses, while its overuse poses environmental challenges. Despite being naturally abundant in soils, phosphorus is often inaccessible to plants due to its tendency to bind with other elements, forming insoluble compounds.

Phosphorus is essential for energy transfer and storage in plants, playing a key role in photosynthesis, respiration, and nutrient transport. It is a vital component of ATP (adenosine triphosphate), the molecule that supplies energy for biochemical processes. It also forms part of phospholipids in cell membranes, ensuring structural integrity and selective permeability.

Moreover, it is essential for DNA and RNA synthesis, as phosphorus is a key part of the phosphate backbone in nucleic acids.

It plays a role in root development and seed formation.

Deficiency symptoms associated with this element include dark green or purplish leaves due to anthocyanin accumulation, reduced root growth, delayed maturity, and poor seed development. Plants absorb phosphorus as phosphate ions ($H_2PO_4^-$ or HPO_4^{2-}), often from soil organic matter or mineral fertilizers.

Phosphorus exists in various forms in the environment, but its bioavailability to plants is limited. The global phosphorus cycle connects terrestrial, aquatic, and atmospheric reservoirs.

Phosphorus originates from the weathering of phosphate-containing rocks, releasing inorganic phosphates into soils and waterways. Unlike nitrogen, phosphorus does not exist in a gaseous phase, making its cycle relatively local.

The key processes in the **phosphorus cycle** include:

- Weathering: phosphorus, primarily found in rocks as phosphate ions ($H_2PO_4^-$ and HPO_4^{2-}), is released into the environment through the breakdown of these rocks by weathering forces like wind, water, and temperature changes, making it available for plants to absorb and enter the food chain; essentially, it's the primary way phosphorus enters the soil from its naturally stored form in rocks.

- Leaching and Runoff: excess phosphorus from soil, often due to fertilizer application, moves into water bodies through two pathways: leaching (water percolating through the soil, carrying dissolved phosphorus deeper into the ground and potentially reaching groundwater) and run-off (surface water flowing over the soil, carrying attached phosphorus particles into nearby waterways) - both contributing to water pollution, especially in the form of algal blooms when phosphorus levels become too high.
- Biological Recycling: Plants and microorganisms incorporate phosphorus into organic compounds, which return to the soil upon decomposition. Plants absorb phosphate from the soil and transfer it to animals that eat them. When plants and animals die or excrete waste, detritivores or the soil can absorb the phosphates. Phosphorus from rivers washes into the ocean, where it's recycled by organisms like plankton and algae. Other organisms consume these organisms, recycling the phosphorus further.

Phosphorus is a key nutrient for all life. Recycling phosphorus from agricultural waste and wastewater can reduce environmental impact and costs.

Phosphorus is absorbed primarily as **inorganic phosphate ions**:

- $H_2PO_4^-$ (Dihydrogen Phosphate): Dominates in acidic soils.
- HPO_4^{2-} (Hydrogen Phosphate): Prevalent in alkaline soils.
- Organic phosphorus, stored in compounds such as phytate and nucleotides, becomes available through microbial activity that breaks down these molecules into inorganic forms.

Only the phosphate anions (HPO_4^{2-} and $H_2PO_4^-$) present in the soil solution can be absorbed by plants. These are often found at concentrations of less than 10 µM. On the other hand, plants have millimolar phosphorus concentrations, or a thousand times higher. Therefore, plants require active, energy-driven transport mechanisms to bring phosphate in against this sharp concentration gradient. Transporter proteins are used to do this. The cytoplasm's pH drops as phosphate is transported into the cell, therefore the cell exports hydrogen ions using a proton pump, which requires energy.

Phosphorus uptake by plants involves intricate mechanisms that ensure its efficient absorption and utilization despite its limited availability in soil.

Plants primarily absorb phosphorus in the form of dissolved phosphate ions (H_2PO^{4-} and HPO_4^{2}) through their root systems, taking it up from the soil solution where concentrations are typically very low, requiring specialized transport systems to actively move it into the root cells; this process is heavily influenced by the plant's root structure and can be enhanced by symbiotic relationships with mycorrhizal fungi which help access more phosphorus in the soil.

The majority of phosphorus uptake occurs through the root hairs and epidermal cells at the root tip. Phosphorus is present in soil solution at very low concentrations, making its uptake challenging for plants. Due to the low concentration gradient, plants need specialized high-affinity transport proteins to actively move phosphorus into the root cells. The optimal pH for phosphorus uptake varies depending on the plant species, but generally, slightly acidic conditions favor absorption. Mycorrhizal fungi can significantly enhance phosphorus uptake by extending their fungal hyphae into the soil, reaching areas that plant roots cannot access. Arbuscular mycorrhizal fungi (AMF) extends hyphal networks into soil, increasing the root's effective absorptive area, and Ectomycorrhizae are particularly effective in nutrient-poor soils.

In addition, phosphorus uptake in cold soil is a challenge for plants due to the reduced mobility and availability of phosphorus in low-temperature conditions. In cold soils, microbial activity decreases significantly, leading to reduced mineralization of organic phosphorus into plant-available inorganic forms (e.g., orthophosphates). Phosphate-solubilizing bacteria and mycorrhizal fungi, which enhance phosphorus availability, also function less effectively in cold temperatures.

The cell membranes of plants include two different kinds of phosphate transporter proteins, each of which functions differently. It is believed that the low-affinity transporters are always present. Phosphate transfer between cells is probably mediated by these transporters as well. Phosphate transporter proteins do not always stay in the membrane, regardless of their affinity level. Instead, they are frequently rotated in reaction to variations in the amount of inorganic phosphate present. It is believed that this mechanism keeps plants from accumulating harmful amounts of P. Phosphate can either be used immediately upon entering cells or saved for later use in vacuoles. For plants to maintain a consistent supply of phosphorus to their cells, this storage facility is necessary. According to studies, between 85 and 95 % of the cellular phosphorus in plants grown in phosphate-sufficient environments is located in the vacuoles. The quantity of phosphorus stored in the vacuoles increases when the amount of phosphate in the environment rises, but not the amount of phosphorus in the cytoplasm.

Mycorrhizal fungi extend from the plant root into the soil, functioning as a massive extension of the root system and allowing access to a much larger area of soil, so boosting the plant's nutritional availability (Figure 4).

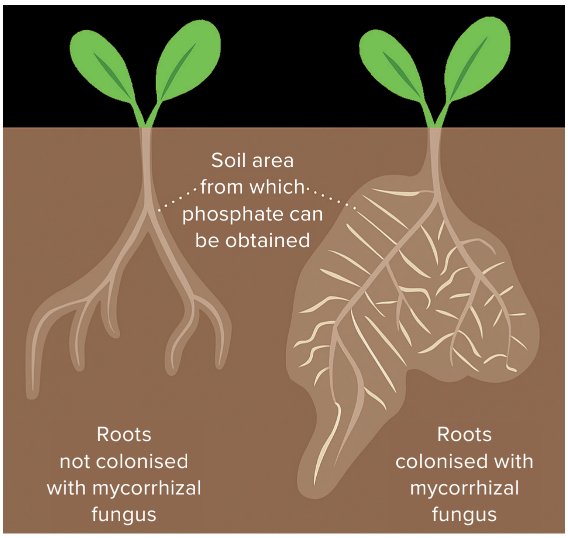

Figure 4: Plant roots infected with arbuscular mycorrhizal fungi are able to source phosphate from a greater soil volume.
Source: https://ballance.co.nz/advice/phosphorus/uptake-by-plants
Own editing

Plants develop specialized root systems to enhance phosphorus acquisition:

- Root Elongation and Branching: Increased root surface area maximizes phosphate interception.
- Root Hairs: Fine structures increase contact with soil particles, enhancing phosphate absorption.
- Cluster Roots (Proteoid Roots): Found in phosphorus-stressed plants like lupines, these roots release organic acids to solubilize bound phosphorus.

The following are the main reasons why **plants lack phosphorus:**

- One of the leading reasons for phosphorus deficiency in plants is the strong chemical fixation of phosphorus in soils. In acidic conditions (low pH), phosphorus binds tightly with iron (Fe) and aluminum (Al), forming insoluble phosphates. In alkaline conditions (high pH), phosphorus reacts with calcium (Ca), producing calcium phosphate, which is also insoluble.
- Many soils naturally contain low levels of phosphorus due to their geological origin. Highly weathered tropical soils, such as those found in parts of Africa, South America, and Asia, are particularly deficient in phosphorus because long-term weathering has depleted phosphate-bearing minerals.
- Topsoil, which contains most of the bioavailable phosphorus, is often lost due to erosion caused by wind or water. The removal of nutrient-rich topsoil significantly reduces phosphorus availability for plants.
- Cold weather slows down microbial activity and the chemical reactions that release phosphorus from organic matter. This is particularly problematic in temperate and boreal regions, where the growing season coincides with cooler conditions.
- In cold soils, diffusion rates decrease due to lower water movement and higher viscosity, making it harder for roots to access available phosphorus.
- In waterlogged conditions, oxygen levels in the soil decrease, leading to anaerobic processes. These conditions can immobilize phosphorus by promoting the formation of insoluble iron and aluminum phosphates. Additionally, water saturation can limit root growth and access to phosphorus in the soil.
- In dry soils, phosphorus becomes less mobile and harder for plants to access. The lack of water reduces the diffusion of phosphate ions through the soil matrix to plant roots, exacerbating phosphorus deficiency during drought periods.
- Soil microbes, such as phosphorus-solubilizing bacteria and fungi, play a critical role in breaking down organic phosphorus compounds and making them available to plants. When microbial activity is low due to environmental stress, organic phosphorus remains locked in forms inaccessible to plants.
- Some plants, especially in disturbed ecosystems or degraded soils, lack associations with mycorrhizal fungi. These fungi extend the effective root system of the plant, enhancing phosphorus uptake. Without these symbiotic relationships, plants are often unable to access sufficient phosphorus.

- Intensive farming practices that involve continuous cropping without adequate replenishment of phosphorus deplete soil phosphorus reserves over time. High-yielding crops extract large amounts of phosphorus from the soil, leading to a gradual decline in its availability.
- Excess phosphorus fertilization can bind with soil minerals or leach into waterways, making it unavailable to plants.
- In many developing regions, farmers lack access to sufficient phosphorus fertilizers, leading to chronic deficiencies in the soil.
- Plants with shallow or poorly developed root systems may struggle to access phosphorus, particularly in soils where phosphorus is localized or bound to deeper layers.

Phosphorus is essential for several core physiological processes in plants, influencing their overall growth and productivity. If the P is in insufficient amount in the soil, **P-deficient symptoms** appear:

- Roots grow slower and may appear shorter or less branched. Plants with phosphorus deficiency often prioritize root growth over shoots, attempting to access phosphorus deeper in the soil.
- Shoots also exhibit reduced elongation and leaf expansion, resulting in smaller, compact plants.
- Limited growth reduces the total biomass of the plant, which can directly translate to reduced crop yields.
- Phosphorus-deficient plants often exhibit leaves that are darker green than normal due to the accumulation of carbohydrates in the foliage. The plant cannot mobilize these sugars effectively to other parts, such as roots and growing tips.
- In severe cases, the leaves develop a purple or reddish hue, especially on the underside. This is due to the accumulation of anthocyanins, a group of pigments produced as a stress response. The purpling is more pronounced in certain crops, such as corn, tomato, and wheat.
- Plants remain in the vegetative growth stage for longer periods as they struggle to acquire sufficient phosphorus to support flowering and fruiting. This delay can make crops more vulnerable to environmental stresses, such as drought or frost, especially in regions with short growing seasons.

Phosphorus is a critical component of adenosine triphosphate (ATP) and other nucleotides that drive energy-dependent biochemical reactions. ATP generated during these processes powers carbon fixation and metabolic pathways.

2.3. Potassium

Potassium (K) is an **essential macronutrient** for plants, required in substantial quantities for optimal growth, development, and productivity. Unlike other macronutrients like nitrogen or phosphorus, potassium does not form part of any specific structural compounds, such as DNA or proteins. Instead, it exists as a soluble ion (K^+) and performs crucial regulatory roles in plant physiology.

Potassium is involved in osmotic regulation, enzyme activation, photosynthesis, nutrient transport, and stress responses (Figure 6).

Its mobility within plants allows it to regulate several critical biochemical pathways and cellular activities:

- Potassium is indispensable for maintaining osmotic potential within plant cells, playing a central role in water uptake and retention. This function underpins several key processes:
  - Its ability to attract water facilitates turgor pressure maintenance, which drives cell elongation and expansion, which is critical for growth.
  - Potassium ions regulate the opening and closing of stomata, which control gas exchange and transpiration. In guard cells, the accumulation of potassium ions leads to osmotic water influx, causing stomata to open. Conversely, potassium efflux promotes stomatal closure. This helps plants conserve water under drought stress by reducing water loss.

Potassium acts as an **activator for over 60 enzymes** involved in various metabolic processes. Examples include:

- Photosynthesis: Enzymes like ribulose-1.5-bisphosphate carboxylase/oxygenase (RuBisCO), which drives carbon fixation, are potassium-dependent.
- Protein synthesis: Potassium activates enzymes that facilitate amino acid incorporation into proteins.
- Respiration: Key enzymes in glycolysis and the citric acid cycle require potassium for optimal function.

Potassium plays a multifaceted role in **photosynthesis**, the cornerstone of plant productivity. However, potassium itself is not a component of the photosynthetic machinery (such as chlorophyll or photosystems), it significantly influences photosynthesis by regulating key physiological and biochemical processes.

Stomata are small openings on the leaf surface that allow gas exchange. Potassium is pivotal in regulating their opening and closing. Potassium ions (K^+) accumulate in guard cells during the day, increasing their osmotic potential. This causes water to flow into the guard cells, making them turgid and opening the stomata (Figure 7). Open stomata allow the entry of carbon dioxide (CO_2), which is essential for the Calvin cycle in photosynthesis. Potassium, therefore, indirectly ensures an adequate supply of CO_2 for carbon fixation. Under potassium deficiency, stomatal function is impaired, reducing CO_2 uptake and limiting photosynthesis.

Potassium activates several enzymes involved in photosynthesis like,

- Ribulose-1.5-bisphosphate carboxylase/oxygenase (RuBisCO): This enzyme catalyzes the fixation of CO_2 in the Calvin cycle, a critical step in photosynthesis. Potassium enhances RuBisCO's activity, ensuring efficient carbon assimilation.
- Phosphoenolpyruvate carboxylase (PEPC): In C_4 and CAM plants, potassium boosts the activity of PEPC, which plays a role in initial carbon fixation.

Without sufficient potassium, the activity of these enzymes declines, reducing the efficiency of photosynthesis.

Potassium facilitates the loading and **transport of photosynthetic products** (sugars) from the source (leaves) to the sink (roots, fruits, and storage organs):

Phloem Loading: Potassium ions create an osmotic gradient in phloem tissues, driving the flow of sugars and other photosynthates.

Feedback Regulation: Efficient sugar transport prevents feedback inhibition of photosynthesis by ensuring that sugars do not accumulate excessively in photosynthetic cells.

Potassium contributes to the stability and efficiency of the photosynthetic machinery. Potassium is essential for **maintaining chlorophyll content and chlorophyll structure**, indirectly supporting light capture and energy transfer in leaves. Its deficiency leads to chlorosis (yellowing), which impairs light absorption and photosynthetic capacity. It also helps stabilize thylakoid membranes, where light-dependent reactions occur, ensuring efficient electron transport and ATP synthesis.

Potassium maintains electrical neutrality within plant cells by balancing the **uptake of anions** like nitrate (NO_3^-) and sulfate (SO_4^{2-}). Potassium enhances root absorption of other nutrients by creating favorable electrochemical gradients. Potassium ions are actively involved in nutrient transport via xylem and phloem tissues, ensuring the distribution of essential ions to growing and storage organs.

Potassium significantly influences a plant's ability to withstand **abiotic and biotic stress.** Under drought, salinity, and temperature extremes, potassium supports osmotic adjustment, antioxidant production, and cell membrane stability. Potassium deficiency increases a plant's susceptibility to pests and pathogens. Adequate potassium levels enhance the synthesis of secondary metabolites and lignin, which fortify plant defenses.

Low-molecular-weight chemicals like soluble sugars, organic acids, amino acids, and amides are less prevalent in the plant tissues of a K-sufficient plant because the synthesis of high-molecular-weight compounds (such proteins, starches, and cellulose) is significantly increased. Potassium-sufficient plants are less susceptible to disease and pest attacks because lower quantities of these low-molecular-weight chemicals are crucial for the development of diseases and insect infestations. Phenol concentrations, which are essential for plant resilience, rise with adequate potassium. Additionally, the synthesis of defense chemicals that result in higher pest mortality and a lack of pest predilection under adequate nutrient concentrations are thought to be the reasons for lower pest damage in higher K plants.

Potassium exists in the soil in three primary forms: unavailable (structural K in minerals), slowly available (exchangeable K), and readily available (soluble K in the soil solution). Plants predominantly absorb potassium in its ionic form (K^+) from the soil solution.

Potassium uptake is mediated by specific potassium transporters and channels located in root cell membranes:

- High-Affinity Systems: Operate under low potassium conditions and are energy-dependent.
- Low-Affinity Systems: Function when potassium concentrations are higher and rely on passive diffusion.

Root hairs and mycorrhizal fungi also play important roles in enhancing potassium uptake by increasing the root's effective surface area.

Once absorbed, potassium is transported to aerial parts via the xylem and distributed to growing tissues, storage organs, and older leaves. Phloem transport of potassium ensures its redistribution to tissues with varying metabolic demands.

Potassium deficiency impairs numerous physiological processes, leading to visible and measurable consequences:

- Growth reduction: Potassium deficiency slows cell expansion and division, resulting in stunted growth.
- Chlorosis and necrosis: Older leaves develop yellowing (chlorosis) along the margins, followed by tissue death (necrosis) due to disrupted photosynthesis and nutrient transport.
- Poor water relations: Inadequate potassium reduces the plant's ability to regulate water loss through stomata, leading to wilting.
- Weak structural integrity: Deficiency compromises cell wall synthesis and lignification, making plants more vulnerable to lodging and mechanical damage.
- Susceptibility to stress: Plants with low potassium are more susceptible to drought, salinity, and pathogen attacks.

Potassium is critical for **agricultural productivity**, influencing crop yield, quality, and resistance to stress. Modern farming heavily depends on potassium fertilizers to meet crop requirements.

Potassium boosts the synthesis and transport of carbohydrates, contributing to higher yields in crops like cereals, fruits, and tubers. Potassium enhances the size, flavor, and shelf life of fruits and vegetables by regulating sugar metabolism and water content. Potassium fertilizers, such as potassium chloride (KCl) and potassium sulfate (K_2SO_4), are widely used in agriculture. However, over-reliance on these fertilizers can lead to environmental concerns, such as soil salinization and water pollution.

Potassium is an essential nutrient with versatile physiological roles, from regulating water relations and enzyme activity to enhancing stress tolerance and nutrient transport. Its unique function as a soluble ion makes it indispensable for plant growth and productivity. Addressing potassium deficiency through sustainable management practices and innovative research is vital for ensuring agricultural sustainability and food security in the face of global challenges. By advancing our understanding of potassium dynamics, we can pave the way for more resilient and efficient crop systems.

2.4. Calcium

Calcium (Ca) is a crucial secondary macronutrient in plants, playing a multifaceted role in cellular processes and overall plant development. It is unique among plant nutrients as it functions predominantly in maintaining structural integrity and signaling, rather than being incorporated into organic molecules like proteins or nucleic acids. Calcium is critical for cell wall formation, membrane stability, ion homeostasis, and intracellular signaling, all of which are integral to plant growth and stress adaptation.

Calcium is required by plants in moderate amounts, typically constituting 0.1–0.5% of their dry weight. Its functions are highly diverse, as it operates both as a structural component and a dynamic regulator of cellular processes.

One of calcium's primary roles is its involvement in maintaining **cellular structure and stability**. Calcium is a vital component of the middle lamella, where it forms calcium pectate. This compound binds pectin molecules together, conferring strength and rigidity to cell walls, which is crucial for maintaining cell shape and preventing mechanical damage. Calcium stabilizes the structure of plasma membranes and organelle membranes by interacting with phospholipids and proteins. It helps maintain membrane integrity and prevents leakage of cellular contents.

Calcium serves as a ubiquitous **secondary messenger** in plant signal transduction pathways. Its ability to function as a signaling molecule stems from its unique properties. Changes in cytosolic calcium levels act as signals that regulate a variety of physiological processes, including growth, development, and stress responses. These changes are often triggered by environmental or hormonal cues. Proteins like calmodulin (CaM) and calcium-dependent protein kinases (CDPKs) bind calcium and mediate downstream responses, such as gene expression and enzymatic activity. Calcium fluxes are critical in plant responses to abiotic stresses like salinity, drought, and temperature extremes, as well as biotic stresses like pathogen attack.

Calcium influences a wide range of cellular processes essential for **plant survival and growth**. Calcium is required for the proper functioning of microtubules and microfilaments during cell division and elongation. Several enzymes, including those involved in metabolic pathways, are activated by calcium ions. Calcium stabilizes membranes and proteins, minimizing damage from temperature extremes. Calcium regulates the organization of the cytoskeleton, which is essential for intracellular transport and cell morphology. In addition during pathogen attack, Ca is signaling activates defense mechanisms, including the production of antimicrobial compounds and reinforcement of cell walls.

Calcium plays a pivotal role in helping plants cope with **environmental stresses**. Under salinity or drought conditions, calcium maintains ion homeostasis and minimizes cellular damage by stabilizing membranes and activating stress-responsive pathways. Calcium signaling mediates the activation of defense responses, including the production of reactive oxygen species (ROS) and pathogenesis-related proteins.

The mobility and availability of calcium in plants are influenced by its chemical properties and transport mechanisms.

Calcium is predominantly present in soil as part of minerals like calcite and gypsum. It is absorbed by plant roots in its ionic form (Ca^{2+}) from the soil solution. However, calcium availability depends on factors such as soil pH, organic matter content, and the presence of competing ions like magnesium and potassium.

Calcium uptake occurs mainly through root apices, where the cell walls are more permeable, and through root hairs. It is absorbed passively along with water movement into the plant via the apoplast or symplast pathways (Figure 5).

The apoplast is the intercellular space between cell membranes filled with gas and water. It also contains the xylem that extends to the rhizoplane and cuticle of the outer plant surface, as well as the interfibrillar and intermicellar spaces of the cell walls. The water and its solutes move through the extracellular space of plants by apoplast pathway.

The symplast is the inner living part of the plant bounded by the plasma membranes. It comprises a complete network of cytoplasm of plant cells connected by plasmodesmata. The symplast lacks cell walls and intercellular spaces. It plays an important role in the transport of water and other low-molecular-weight solutes, such as sugars, amino acids, and ions, between cells.

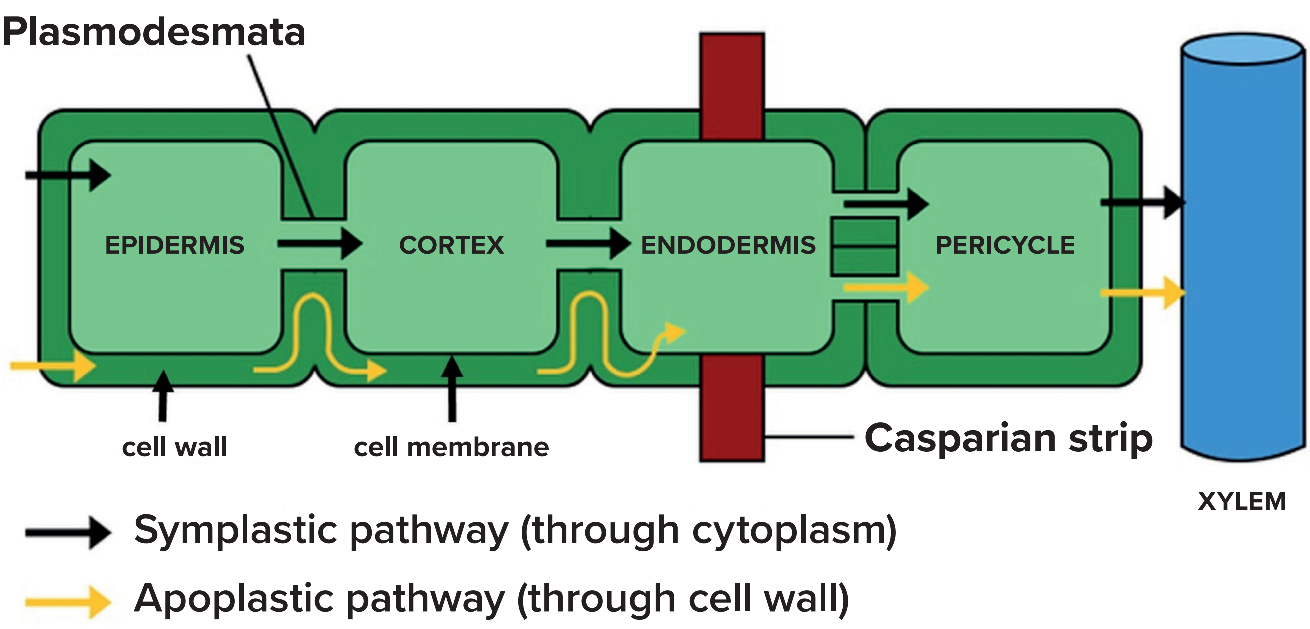

Figure 5: Symplastic and apoplastic pathway in plants
Source: https://www.geeksforgeeks.org/apoplast-vs-symplast-pathway-differences-explained/
Own editing

Once absorbed, calcium is transported through the xylem to aerial parts of the plant. However, calcium transport is largely unidirectional due to its limited mobility in the phloem. This immobility leads to the accumulation of calcium in older tissues, while younger tissues rely on a steady supply via the xylem.

The main **physiological roles of calcium** are the following:

- Calcium is essential for root growth and function. Calcium maintains the structural integrity of the root apex, where active cell division and elongation occur. Adequate calcium levels are required for the proper formation and elongation of root hairs, which enhance nutrient and water absorption.

- Plays a significant role in shoot growth and leaf health. Calcium supports the activity of apical meristems in shoots, facilitating shoot elongation and branching. Ca-deficiency can lead to disorders like blossom-end rot in tomatoes and tip burn in lettuce, highlighting its importance in shoot and leaf health.
- Indispensable for reproduction in plants. Calcium ions regulate the germination of pollen grains on the stigma. The growth and directional movement of pollen tubes are guided by calcium gradients, which ensure successful fertilization.

Calcium **deficiency** manifests in various physiological and developmental abnormalities;

- Deficiency weakens cell walls, leading to symptoms like tissue collapse and necrosis.
- Stunted growth and reduced root hair development are common signs of calcium deficiency.
- Specific disorders caused by calcium deficiency include:
- Characterized by the decay of tissues at the bottom of fruits like tomatoes and peppers (blossom-end rot).
- Occurs in leafy crops like lettuce and cabbage, resulting in necrotic leaf edges (tip burn).
- Calcium-deficient plants are more susceptible to abiotic and biotic stresses due to impaired signaling and membrane stability.

Calcium plays an indispensable role in plant physiology, influencing structural stability, intracellular signaling, stress adaptation, and development. Its contributions to cell wall integrity, membrane stabilization, and signal transduction make it essential for plant growth and productivity. Calcium deficiency can severely impair plant health, leading to reduced yields and quality. To meet the demands of modern agriculture, sustainable calcium management practices and advances in calcium research are crucial. By leveraging these strategies, we can ensure food security and agricultural sustainability in a changing world.

2.5. Magnesium

Magnesium (Mg) is an essential macronutrient for plants, playing critical roles in various physiological and biochemical processes. As a central component of chlorophyll and an activator of numerous enzymes, magnesium is indispensable for photosynthesis, energy metabolism, and nutrient transport. Despite being required in relatively small amounts compared to other macronutrients, magnesium deficiency significantly impacts plant growth and productivity.

Magnesium's role in plant physiology is multifaceted, influencing structural, enzymatic, and transport processes critical for growth and development.

Vital role in photosynthesis:

- Magnesium is the central atom in the **chlorophyll** molecule, coordinating with nitrogen atoms to form the chlorophyll ring structure. Chlorophyll is the pigment responsible for capturing light energy during photosynthesis, making magnesium essential for this process. Without adequate magnesium, the efficiency of light capture and energy conversion diminishes, severely affecting photosynthetic capacity. Porphyrin is the precursor to chlorophyll. There is a magnesium atom in the core of chlorophyll's chemical structure.

- In addition, there are four nitrogen atoms surrounding the magnesium. Four carbons plus nitrogen make up the pyrrole ring structure. There is also a hydrocarbon end visible. The porphyrin head is the collective term for the four pyrrole rings that contain magnesium and nitrogen. The phytol tail is the hydrocarbon end.
- Magnesium is integral to the **photosynthetic process**. As the central atom of chlorophyll, magnesium is directly involved in light absorption. Magnesium stabilizes ATP and supports the activity of ATP synthase during photophosphorylation. Magnesium helps activate RuBisCO (ribulose-1,5-bisphosphate carboxylase /oxygenase), the main enzyme for capturing carbon dioxide, and other enzymes in the Calvin cycle, allowing plants to turn carbon dioxide into sugars.

In addition to its role in Calvin cycle during photosynthesis, magnesium **activates over 300 enzymes** involved in critical metabolic pathways such as:

- Protein synthesis: Magnesium stabilizes ribosome structures and facilitates protein biosynthesis.
- Energy metabolism: It plays a vital role in glycolysis, the citric acid cycle, and the synthesis of ATP by stabilizing the ATP molecule and its interactions with enzymes.

Magnesium is integral to ATP, the universal **energy carrier** in biological systems. ATP exists in cells as a complex with magnesium (Mg-ATP), which is essential for its stability and functionality. Magnesium-dependent enzymes facilitate energy transfer processes, including phosphorylation reactions in photosynthesis and respiration.

Magnesium regulates the **movement of nutrients and carbohydrates** within the plant. It facilitates the loading and unloading of sugars in the phloem, ensuring efficient transport from source tissues (leaves) to sink tissues (roots, fruits, and seeds). Magnesium also helps maintain cation balance, interacting with potassium (K^+) and calcium (Ca^{2+}) to regulate ion homeostasis. Magnesium contributes to the structural stability of nucleic acids (DNA and RNA) by neutralizing negative charges on phosphate groups. It stabilizes membranes by interacting with phospholipids and proteins, thus maintaining cell integrity.

Magnesium helps to control production of harmful molecules called reactive oxygen species (ROS) during stresses like drought, salty soil, and heat. It also helps plants to make antioxidants like glutathione and ascorbate, which protect them from ROS damage.

Magnesium exists in the soil as part of minerals (e.g., dolomite and magnesite) or in soluble form as Mg^{2+} ions in the soil solution.

Its availability depends on soil pH, texture, and the presence of competing cations like calcium (Ca^{2+}) and potassium (K^+).

Plants absorb magnesium from the soil solution in its ionic form (Mg^{2+}) through both passive diffusion and active transport mechanisms.

High-affinity magnesium transporters, such as members of the MGT (magnesium transporter) family, facilitate uptake, especially under low magnesium conditions.

Magnesium is transported from roots to shoots via the xylem. It is highly mobile in plants and can be redistributed to younger tissues when necessary. In the phloem, magnesium facilitates the transport of sugars and other metabolites to growing tissues and storage organs.

Magnesium **deficiency** has profound effects on plant physiology, often manifesting as visible symptoms and impaired metabolic functions.

- Yellowing of the leaf tissue between veins, while the veins remain green, is a classic symptom (intervenial chlorosis).
- Prolonged deficiency can lead to tissue death at the leaf margins or tips (necrosis).
- In some plants, magnesium deficiency causes leaf edges to curl upward or downward.
- Stunted growth in both roots and shoots is a common symptom of magnesium deficiency.
- Magnesium deficiency reduces chlorophyll content, leading to impaired light capture and photosynthetic efficiency.
- It also disrupts the functioning of the photosynthetic apparatus, including electron transport and ATP synthesis.
- A lack of magnesium hinders phloem loading and sugar transport, causing carbohydrate accumulation in leaves and inadequate supply to roots and fruits.
- Magnesium-deficient plants are more vulnerable to abiotic stresses (e.g., drought and salinity) and biotic stresses (e.g., pathogen attacks), as they lack sufficient energy reserves and antioxidant capacity.

Magnesium enhances crop yield by supporting photosynthesis, nutrient transport, and stress tolerance. It improves the quality of fruits, vegetables, and grains by ensuring optimal sugar transport and storage. Magnesium is supplied to crops through fertilizers like magnesium sulfate (Epsom salts) and dolomite lime. Balanced fertilization, including magnesium, is crucial for maintaining soil fertility and preventing nutrient imbalances. Regular soil testing helps determine magnesium availability and informs fertilization practices. Including magnesium-demanding crops in rotation can improve magnesium use efficiency. Developing slow-release magnesium fertilizers and biofertilizers can enhance magnesium availability and uptake. Research into magnesium's role in stress resilience is critical for developing crops that can thrive under changing environmental conditions.

Magnesium is a cornerstone of plant physiology, influencing processes ranging from photosynthesis and enzyme activation to nutrient transport and stress tolerance. Its role as the central atom in chlorophyll and a stabilizer of ATP shows its importance in energy metabolism and growth. Magnesium deficiency poses significant challenges to plant health, leading to reduced productivity and increased susceptibility to stress. By advancing our understanding of magnesium dynamics in plants and implementing sustainable management practices, we can optimize crop yields and ensure agricultural sustainability in the face of global challenges.

2.6. Sulfur

Sulfur (S) is an essential macronutrient required for key physiological and biochemical processes in plants. Although needed in smaller amounts than nitrogen, phosphorus, and potassium, it is crucial for producing amino acids like cysteine and methionine (Figure 16), as well as proteins, vitamins, and secondary metabolites. Sulfur supports protein synthesis, enzyme activity, stress resistance, and metabolic regulation, playing both structural and regulatory roles in plant functions.

As the sole metabolic sulfide donor for the production of methionine, glutathione, phytochelatins, iron-sulfur clusters, vitamin cofactors, and several secondary metabolites, cysteine biosynthesis is essential to plants' ability to fix inorganic sulfur from the environment.

Cysteine is a structural component of proteins and is a precursor to many biomolecules, including vitamins, cofactors, antioxidants, and defense compounds. It plays a significant role in plant immunity, especially in the cytosol. In the mitochondria, cysteine plays a key role in detoxifying cyanide, which is important for root hair development and plant responses to pathogens. Cysteine and related molecules, such as sulfide, S-sulfocysteine, and cyanide, act as signaling molecules that regulate many plant processes, including photosynthesis, plant protection, plant immunity, autophagy, and root development. Cysteine proteinases, also known as thiol proteases, play a role in plant growth and development, senescence, programmed cell death, and the accumulation and mobilization of storage proteins. The disulfide bonds (S-S bonds) formed between cysteine residues stabilize the three-dimensional structure of proteins, ensuring their proper function.

Methionine is naturally low in plants, which reduces its nutritional value for humans and animals. It is a building block for proteins and a precursor for many sulfur-containing compounds. Methionine plays a key role in stabilizing protein structures, acting as an antioxidant, and initiating protein synthesis. It is also the precursor to S-adenosylmethionine (SAM), a universal methyl donor involved in DNA methylation, ethylene production, and the regulation of polyamines and biotin. Additionally, SAM metabolism is linked to plant growth hormones like auxin and cytokinins and serves as a transport molecule for reduced sulfur in some plants.

Sulfur-containing amino acids and cofactors are critical for the activation and function of several enzymes. Fe-S (iron-sulfur) clusters in enzymes facilitate electron transport in photosynthesis and respiration. Coenzyme A (CoA) and biotin, both sulfur-containing cofactors, are involved in fatty acid and carbohydrate metabolism.

Sulfur is also required for the synthesis of chloroplast proteins and cofactors, influencing chlorophyll production and overall photosynthetic efficiency. Fe-S clusters in proteins of the photosynthetic electron transport chain (e.g., ferredoxin) are essential for transferring electrons.

Sulfur is a key component of several secondary metabolites that have protective and regulatory roles:

- Glucosinolates found in brassicas (e.g., cabbage, broccoli), glucosinolates provide defense against pests and pathogens.
- Alliin and Allicin in Allium species like garlic and onions, sulfur-containing compounds confer antimicrobial and health-promoting properties.
- Phytochelatins as sulfur-rich peptides that chelate heavy metals, protecting plants from metal toxicity.

Sulfur also helps plants **cope with biotic and abiotic stresses**. Sulfur is a precursor for glutathione (GSH), a tripeptide that protects cells from oxidative stress by scavenging reactive oxygen species (ROS). Sulfur-containing compounds like glucosinolates and elemental sulfur deposits enhance resistance to pathogens.

There is a lot of sulfur in some agricultural soils. To guarantee healthy, fruitful crops, sulfur fertilizer must be added to those that are lacking. Like phosphorus, sulfur is thought to make up around 0.05% of the earth's crust on average. Sulfur exists in soil as inorganic sulfate (SO_4^{2-}), organic sulfur compounds, and in gaseous forms (e.g., hydrogen sulfide, H_2S). Approximatly 90% is organic and 10% is inorganic sulfur. Human activity emerges as a major contributor to sulfur emissions due to industrialization. Sulfur dioxide (SO_2) is released into the atmosphere during the production, refining, and burning of hydrocarbons like coal, crude oil, natural gas, and oil sands. Initially, sulfur from this source helped boost agricultural output as it was returned to the earth through precipitation (Figure 18). However, in the 1980s, scientists warned that H_2S was causing serious harm to the environment. As a result, regulations were introduced to significantly reduce industrial emissions. Years later, agriculture that once had an abundance of this macronutrient is now experiencing deficits due to the decrease in atmospheric sulfur. Sulfur fertilizers are now more necessary as a result of this. Ironically, inert organic sulfur is a byproduct of the Claus Process, which was created to eliminate H_2S from the extraction and refining of oil and gas. Today, almost all manufactured sulfur fertilizers come primarily from this source.

Plants primarily absorb sulfur in the inorganic form of sulfate (SO_4^{2-}) from the soil solution. Elemental sulfur cannot be used by plants. Soluble sulfate (SO_4^{2-}), which they need, is taken up by roots. Sulfates are regarded as an inorganic sulfur form. Adsorbed sulfates, which are released more slowly and are typically found in the subsoil, and readily soluble sulfates are two types of sulfates.

More than 90% of sulfur in soils naturally occurs in organic forms, but this doesn't mean plants can't use it. Soil microbes help transform organic sulfur into sulfate, which plants can absorb. These microbes feed on organic sulfur, oxidizing it to create soluble sulfate. This gradual transformation ensures a steady supply of sulfur throughout the growing season. In colder regions, such as Canada and the Northern United States, sulfur oxidation slows down in winter, as microbes become dormant and year-round cropping is not practiced. In these conditions, elemental sulfur fertilizer remains intact and is not prone to leaching, even if winter weather helps break down sulfur particles into the ideal size for microbial activity.

Sulfur fertilizers are essential for sulfur-deficient soils to produce high-quality, high-yield crops, particularly for oilseeds and other crops with high sulfur needs. Sulfate fertilizers, such as gypsum (calcium sulfate), potassium sulfate, ammonium sulfate (AMS or AS), single superphosphate (SSP), and potassium and magnesium sulfate, provide sulfur that is immediately available to plants. Liquid sulfur fertilizers like calcium thiosulfate, potassium thiosulfate, and ammonium thiosulfate are also viable options. Ammonium sulfate and elemental sulfur-bentonite fertilizers are the most cost-effective sulfur fertilizers for sulfur deficiencies, meeting the needs for crops with high sulfur requirements, and pH adjustments. A sulfate and elemental products are frequently used in combination by farmers, who apply a modest amount of AMS during the early stages of the crop and rely on bacteria to convert elemental sulfur, which becomes available throughout the crop season. Regular elemental sulfur application as part of a yearly fertility strategy can help people become less dependent on AMS or replace it completely.

Sulfate is taken up actively by sulfate transporters located in the root cell membranes.

These transporters operate under varying sulfur availability:

- High-Affinity Transporters: Function in low-sulfur conditions to maximize uptake.
- Low-Affinity Transporters: Operate when sulfur is abundant.

Once inside the plant, sulfate is reduced and incorporated into organic molecules through the **sulfur assimilation pathway**:

- Reduction: Sulfate is reduced to sulfide (S^{2-}) in the chloroplasts via enzymatic reactions, including the action of ATP sulfurylase and sulfite reductase.
- Incorporation: Sulfide is incorporated into cysteine, which serves as the precursor for other sulfur-containing compounds, including methionine, glutathione, and secondary metabolites.

Sulfur deficiency significantly impacts plant growth, productivity, and resilience. The symptoms often resemble nitrogen deficiency but are more pronounced in younger leaves.

Yellowing of younger leaves due to reduced chlorophyll synthesis. Sulfur deficiency hinders protein synthesis, leading to reduced cell division and elongation. Deficient plants often exhibit weak stems and underdeveloped root systems. Sulfur deficiency impairs chlorophyll production, reducing photosynthetic efficiency. It also disrupts the electron transport chain, further lowering energy production. Reduced glutathione levels compromise antioxidant defenses, leaving plants more susceptible to oxidative stress and pathogen attacks. In crops like onions, garlic, and mustard, sulfur deficiency reduces the production of sulfur-containing compounds, affecting flavor, aroma, and nutritional quality.

Sulfur is critical for achieving high yields and quality in various crops. Its role in agriculture extends from improving nutrient use efficiency to enhancing crop resilience.

Sulfur is applied to crops in various forms, including elemental sulfur, sulfate-containing fertilizers (e.g., ammonium sulfate, potassium sulfate), and gypsum. Sulfur enhances the efficiency of nitrogen utilization by supporting protein synthesis and balancing the C:N ratio in plants.

Certain crops have a higher sulfur requirement due to their reliance on sulfur-containing compounds. Canola and sunflower require sulfur for oil synthesis and quality. Cabbage, broccoli, and mustard rely on sulfur for glucosinolate production. Onions and garlic need sulfur for the synthesis of flavor compounds.

Sulfur deposition from industrial emissions has declined due to stricter pollution controls, leading to an increased reliance on sulfur fertilization. Sustainable management practices, such as soil testing and precision agriculture, are essential for maintaining optimal sulfur levels in agricultural systems.

Research into sulfur assimilation and metabolism is uncovering the regulatory mechanisms governing sulfur-responsive genes and enzymes. Insights into these pathways can inform breeding programs aimed at improving sulfur efficiency in crops. Genetic engineering and marker-assisted breeding are being used to develop crop varieties with enhanced sulfur uptake and utilization. Biofertilizers containing sulfur-oxidizing bacteria offer a sustainable solution for improving sulfur availability in soils. Sulfur's role in stress tolerance makes it a critical nutrient for developing crops that can withstand the challenges posed by climate change, such as increased salinity, drought, and pest pressure.

Sulfur contributes to protein synthesis, photosynthesis, stress adaptation, and the production of essential secondary metabolites. Its deficiency can severely impair plant growth, productivity, and resilience, making sulfur management a vital component of modern agriculture. Advances in sulfur research, coupled with sustainable fertilization practices, hold the key to optimizing sulfur use in crops and ensuring agricultural sustainability in the face of global challenges. By understanding and leveraging sulfur's physiological roles, we can enhance crop quality, yield, and environmental resilience.

3.
Plant Physiological Effects of Essential Micro Elements Found in Industrial Wastes and By-Products

Microelements, also known as micronutrients, are essential elements required in small quantities by plants for their growth, development, and physiological processes. Although they are needed in minute amounts, their absence or imbalance can lead to severe physiological disorders and reduced plant productivity. Microelements include elements such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni).

These microelements act as **cofactors for numerous enzymes**, enhancing their catalytic activity. For instance, zinc activates over 300 enzymes, while manganese participates in activating dehydrogenases and decarboxylases. Copper and iron are central to redox reactions due to their variable oxidation states.

Microelements like boron and zinc influence **structural integrity** and **growth**. Boron thens cell wall formation, while zinc regulates growth hormones like auxins. Copper contributes to lignin synthesis, enhancing structural strength.

Microelements can also **protect plants against oxidative stress** and environmental challenges. Manganese and copper are components of superoxide dismutase, an enzyme that detoxifies reactive oxygen species. Zinc stabilizes membranes and reduces oxidative damage, while iron activates catalase and peroxidase enzymes.

Overall, micronutrients play a significant role in **sustainable agriculture** by enhancing crop yield and quality.

Balanced micronutrient management:

- Improves Yield: Supports functional physiological and metabolic processes, leading to higher productivity.
- Enhances Nutritional Value: Improves the micronutrient content of crops, contributing to human and animal nutrition.
- Mitigates Environmental Stress: Increases plant resilience to biotic and abiotic stresses, reducing crop losses.

3.1. Iron

Iron (Fe) is an essential micronutrient for plant growth and development. It plays a crucial role in various physiological and biochemical processes, including photosynthesis, respiration, and the synthesis of key macromolecules. Despite being abundant in the Earth's crust, iron is often unavailable to plants due to its low solubility in soil, especially under aerobic and high pH conditions.

Iron is a vital element for plants due to its involvement in several fundamental physiological processes. It is integral to the electron transport chain of **photosynthesis**, where it participates in the transfer of electrons in photosystem I and II. Iron-containing proteins, such as ferredoxins and cytochromes, are key components of these systems, enabling energy capture and conversion during light-dependent reactions.

Iron is a component of cytochromes and iron-sulfur clusters in mitochondria, which facilitates electron transport in **oxidative phosphorylation**. This process is crucial for ATP synthesis, providing the energy required for cellular metabolism. Iron also contributes to chlorophyll production, as it activates enzymes involved in the synthesis of chlorophyll precursors. In nitrogen-fixing plants, iron is a **cofactor** for nitrogenase, the enzyme responsible for converting atmospheric nitrogen into ammonia. This process is vital for leguminous plants and contributes to soil fertility. Moreover, iron plays a role in the **detoxification of reactive oxygen species** (ROS) by being a cofactor for enzymes such as catalase and peroxidase. These enzymes protect plants from oxidative stress caused by environmental challenges.

Iron uptake in plants is a tightly regulated process that ensures plants have enough iron for growth while preventing toxicity. Plants use a variety of **mechanisms to absorb iron** from the soil, transport it to their shoots, and store it in their cells.

Strategy I plants use a reduction-based mechanism to absorb iron from the soil. This strategy is used by non-graminaceous plants, such as Arabidopsis and tomato. Root cells release protons H^+ to lower the soil pH and increase the solubility of Fe^{3+} ions. A membrane-bound reductase reduces Fe^{3+} ions to Fe^{2+} ions. A high-affinity transporter in the root membrane absorbs Fe^{2+} ions.

Strategy II iron uptake mechanism used by primarily grasses like rice and maize, to acquire iron from the soil by secreting molecules called phytosiderophores, which chelate (bind to) iron ions, making them readily available for uptake by the plant roots. This strategy is distinct from strategy I where plants primarily rely on lowering the pH of the rhizosphere to reduce ferric iron for uptake.

Once absorbed, iron is transported within the plant to meet the demands of various tissues and organelles.

The transport process includes:

- Loading into the Xylem: Iron is complexed with citrate or other organic acids for translocation via the xylem.
- Phloem Transport: Iron moves through the phloem to developing tissues, including young leaves and reproductive organs.
- Subcellular Distribution: Iron is delivered to chloroplasts, mitochondria, and other organelles where it is incorporated into functional proteins.

Key proteins involved in iron transport include:

- Ferritins: Store excess iron in a non-toxic form.
- Iron-Sulfur Cluster Assembly Proteins: Facilitate the incorporation of iron into iron-sulfur clusters, which are essential for enzyme function.

Iron deficiency, or iron chlorosis, is a common plant disorder that mainly affects young leaves and causes the following symptoms:

- Yellowing of leaves with green veins (interveinal chlorosis) due to impaired chlorophyll production.
- Reduced leaf size and overall plant growth.
- Poor flowering and fruit development due to limited energy production.

These deficiencies are common in calcareous soils with high pH, where iron is less soluble, and in waterlogged soils, where low oxygen levels decrease iron availability. Iron deficiency is a significant challenge in agriculture, especially in areas with alkaline soils.

Application of ammonium sulfate or sulfur reduces soil pH, increasing iron solubility. Compost and organic amendments release chelating agents that enhance iron availability. Use of iron sulfate or chelated iron (e.g., Fe-EDDHA) provides readily available iron to plants. Breeding crops with enhanced iron uptake and utilization capacity is a sustainable solution. Overexpression of genes involved in phytosiderophore production, iron transport, and storage has been explored to develop biofortified crops with improved iron content. Spraying iron solutions directly onto leaves bypasses soil-related limitations and provides immediate relief from deficiency symptoms.

Iron deficiency anemia affects a significant portion of the global population, particularly in developing countries. Iron biofortification of staple crops offers a sustainable approach to addressing this issue. Increasing the iron content in rice, wheat, and maize through conventional breeding and genetic modification. Reducing anti-nutritional factors such as phytates that inhibit iron absorption.

While iron is essential, excessive iron can be toxic to plants. High concentrations of free iron catalyze the formation of hydroxyl radicals through Fenton reactions, leading to oxidative damage. Plants mitigate this **risk** through:

- Excess iron is sequestered in ferritin proteins within plastids.
- Plants down-regulate iron transporters when internal levels are sufficient.

3.2. Zinc

Zinc (Zn) is a vital micronutrient for plants, playing a central role in numerous physiological and biochemical processes necessary for growth, development, and reproduction. Although required in small amounts, zinc is indispensable for plant health due to its involvement in enzymatic functions, protein synthesis, hormonal regulation, and protection against oxidative stress.

Zinc is a transition metal with unique properties that make it essential for various plant metabolic processes. It plays structural, catalytic, and regulatory roles in biomolecules and supports key functions, including:

- Enzyme Cofactor: Zinc is vital for over 300 enzymes, aiding in metabolic activities such as converting carbon dioxide and bicarbonate for photosynthesis and respiration. It also supports anaerobic respiration under stress conditions.
- Antioxidant Defense: As part of superoxide dismutase (Zn-SOD), zinc helps detoxify the ROS, protecting plants from oxidative damage.
- Protein Synthesis: Zinc stabilizes ribosomes, ensuring efficient protein production, and regulates enzymes involved in RNA and DNA metabolism, promoting cell growth and division.
- Hormone Regulation: Zinc is crucial for producing indole-3-acetic acid (IAA), a key auxin that controls cell elongation and division. It also influences the biosynthesis and activity of other growth hormones.
- Membrane Stability: Zinc stabilizes cell membranes by protecting phospholipids and proteins, ensuring efficient nutrient transport and signal transduction.
- Stress Protection: Zinc activates antioxidant enzymes, enhancing the plant's ability to withstand stressors like drought, salinity, and pathogens.

Zinc is absorbed by plant roots as Zn^{2+} ions from the soil solution. The **uptake and transport** processes involve complex mechanisms to ensure efficient acquisition and distribution.

Zinc uptake is facilitated by specific zinc transporter proteins belonging to the ZIP (Zinc-Regulated Transporter/Iron-Regulated Transporter-like Protein) family. These transporters mediate the influx of Zn^{2+} ions into root cells. Zinc availability in soil is influenced by pH, organic matter content, and the presence of competing cations. Acidic soils favor higher zinc solubility, while alkaline or calcareous soils reduce its availability.

Once absorbed, zinc is chelated with organic acids or amino acids and transported via the xylem to aerial parts of the plant. Zinc is redistributed to developing tissues, seeds, and reproductive organs through the phloem.

Zinc is **stored** in vacuoles and chloroplasts, where it participates in metabolic reactions and serves as a reservoir for cellular homeostasis.

Zinc **deficiency** is one of the most widespread micronutrient disorders in plants, particularly in calcareous, sandy, or highly weathered soils. Interveinal chlorosis, characterized by yellowing between leaf veins, is a common sign of zinc deficiency (Figure 20). This is due to impaired chlorophyll synthesis. Zinc deficiency reduces cell elongation and division, leading to smaller leaves, shortened internodes, and overall stunted growth. Flowering and fruiting are adversely affected, with smaller seeds, reduced pollen viability, and low grain yield. Leaves may exhibit a rosette-like appearance, curling, or necrotic spots due to disrupted auxin synthesis and distribution.

While zinc is essential, excessive amounts can lead to **toxicity**, causing adverse effects. High zinc concentrations interfere with membrane stability and ion transport. Excess zinc competes with iron, manganese, and copper for uptake, leading to secondary deficiencies. Elevated zinc levels can generate ROS, causing cellular damage.

Zinc plays a vital role in enhancing **plant resilience** to various abiotic and biotic stresses. It contributes to osmoregulation and maintains membrane integrity under water-deficit and high-salinity conditions. It also activates antioxidant enzymes, reducing oxidative damage. Zinc boosts the synthesis of phytoalexins and pathogenesis-related proteins, improving plant defense against pathogens. It also helps mitigate the toxicity of heavy metals like cadmium by enhancing chelation and sequestration mechanisms.

Given the prevalence of zinc deficiency, several approaches can enhance zinc availability and uptake. Application of zinc sulfate or zinc oxide improves zinc availability in deficient soils. Adding compost or manure enhances zinc solubility by releasing chelating agents. Lowering soil pH with sulfur or ammonium-based fertilizers increases zinc solubility. Spraying zinc-containing solutions on leaves bypasses soil limitations and provides immediate relief from deficiency symptoms. Breeding crops with enhanced zinc uptake and utilization efficiency is a sustainable approach to addressing zinc deficiency. Developing zinc-enriched crops through conventional breeding or genetic engineering improves both plant nutrition and human health. Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi enhance zinc solubilization and uptake by roots, offering a biological solution to zinc deficiency.

Zinc is critical for **sustainable agriculture** due to its role in improving crop yield and quality. Adequate zinc nutrition enhances photosynthesis, protein synthesis, and reproductive success, leading to higher yields. Zinc-enriched crops have better nutritional profiles, addressing zinc deficiencies in human diets. Efficient zinc management reduces the need for excessive fertilizer use, minimizing environmental pollution.

Zinc deficiency is a major global health issue, affecting nearly one-third of the world's population. Biofortification of crops is a promising strategy to alleviate this problem. Fortifying staple foods like rice, wheat, and maize with zinc improves dietary intake. Reducing anti-nutritional factors such as phytates enhances zinc absorption in humans.

Advancements in zinc research aim to address challenges in zinc nutrition and utilization. Identifying genes involved in zinc uptake, transport, and homeostasis offers insights into improving plant zinc efficiency. Nano-zinc fertilizers provide targeted and efficient delivery of zinc to plants, reducing environmental impact. Manipulating soil microbiota to enhance zinc solubilization and uptake is a promising area of research.

3.3. Manganese

Manganese (Mn) is an essential micronutrient for plants, playing a pivotal role in various physiological and biochemical processes. Although required in trace amounts, manganese is indispensable for plant growth, development, and resistance to environmental stresses. It is involved in enzyme activation, photosynthesis, redox reactions, and the synthesis of secondary metabolites.

Manganese is a transition metal with multiple oxidation states, allowing it to participate in redox reactions and act as a cofactor for various enzymes.

Manganese plays a critical role in the **photosynthetic process** by being an essential component of the oxygen-evolving complex (OEC) of Photosystem II. The OEC, also known as the water-splitting complex, uses manganese to catalyze the splitting of water molecules into oxygen, protons, and electrons:

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2$$

This reaction provides the electrons needed to drive the light-dependent reactions of photosynthesis.

Manganese **activates several enzymes** involved in critical metabolic pathways, including:

- Decarboxylases and dehydrogenases: These enzymes participate in organic acid metabolism and the tricarboxylic acid (TCA) cycle.
- Superoxide dismutase (Mn-SOD): This enzyme scavenges reactive oxygen species (ROS), protecting plants from oxidative stress.
- Arginase: Involved in nitrogen metabolism, it catalyzes the hydrolysis of arginine into urea and ornithine.

Manganese also regulates the synthesis of **secondary metabolites**, such as lignin, which strengthens cell walls and contributes to structural integrity. It is also involved in the production of phenolic compounds that aid in plant defense. Manganese affects the biosynthesis and activity of plant hormones, particularly auxins, which influence cell elongation and division. It is also vital for the assimilation of nitrogen and the fixation of carbon through its involvement in enzymes like nitrate reductase and pyruvate carboxylase.

Plants take in manganese mainly as Mn^{2+} ions from the soil, with the process influenced by soil properties, transporter proteins, and the plant's needs. Manganese is absorbed through two systems:

- High-Affinity Transport: Specialized manganese transporters, like those in the NRAMP family, actively facilitate the uptake of Mn^{2+} into root cells.
- Low-Affinity Transport: Allows Mn^{2+} ions to passively diffuse into root cells.

These systems ensure plants can meet their manganese requirements under varying conditions.

Soil pH, redox potential, and organic matter content significantly affect manganese availability. Acidic and waterlogged soils enhance manganese solubility, while calcareous soils with high pH reduce its bioavailability.

After uptake, manganese is **transported** to shoots via the xylem. It forms complexes with organic acids or amino acids, which stabilize it during translocation.

Manganese is **distributed** to chloroplasts, mitochondria, and other organelles where it performs its physiological functions. It is also stored in vacuoles to prevent toxicity.

Manganese **deficiency** is common in soils with high pH, excessive organic matter, or poor drainage. One of the hallmark signs of manganese deficiency is the yellowing of leaf tissue between the veins, primarily in young leaves, while the veins remain green. Severe manganese deficiency results in the development of brown or black necrotic lesions on leaves due to impaired metabolic processes. Since manganese is essential for Photosystem II, its deficiency disrupts the photosynthetic process, leading to reduced plant vigor and stunted growth. Manganese deficiency can lead to weak root systems, limiting the plant's ability to absorb water and nutrients.

While manganese is crucial, excessive levels can be **toxic** to plants. Toxicity typically occurs in acidic or waterlogged soils where manganese solubility is high. Manganese toxicity causes the development of dark spots and bronzing of older leaves. Excess manganese disrupts cell division and expansion, leading to deformed leaves. High manganese concentrations interfere with the uptake of other essential nutrients, such as iron, calcium, and magnesium. Manganese toxicity generates oxidative stress by promoting the production of ROS, leading to cellular damage and impaired metabolic functions.

Manganese also contributes significantly to plant **resilience** under environmental stresses. The activation of manganese-dependent superoxide dismutase (Mn-SOD) reduces the accumulation of ROS, protecting plants from oxidative damage caused by drought, salinity, and heavy metal toxicity. Manganese enhances the synthesis of lignin and phenolic compounds, strengthening plant cell walls and providing a physical and chemical barrier against pathogens. Mn influences the sequestration of toxic heavy metals, reducing their bioavailability and toxicity to plants.

Ensuring adequate manganese nutrition is critical for plant health and productivity. Lowering soil pH through the application of sulfur or ammonium-based fertilizers increases manganese solubility. Adding compost or manure enhances manganese availability by releasing chelating agents that bind to Mn^{2+}. Preventing waterlogging reduces the risk of manganese toxicity.

Soil application of manganese sulfate or manganese oxide can correct deficiencies. Applying manganese-containing solutions directly to leaves provides a rapid remedy for deficiency symptoms. Breeding crops with enhanced manganese uptake and utilization efficiency is a sustainable solution for managing deficiencies. Overexpression of manganese transporter genes can improve manganese acquisition and distribution in plants.

Manganese management is integral to **sustainable farming** practices. Adequate manganese nutrition supports photosynthesis, enzyme activity, and stress tolerance, leading to higher crop yields. Manganese influences the synthesis of compounds that enhance flavor, texture, and nutritional value. Efficient manganese management reduces the risk of runoff and soil contamination. Recent advancements in manganese research aim to address challenges related to its availability and utilization. Nano-manganese fertilizers enhance the efficiency of manganese delivery to plants while minimizing environmental impact. Understanding the role of soil microorganismsin manganese solubilization can lead to the development of biofertilizers. Identifying genes involved in manganese transport and homeostasis offers insights into improving plant manganese efficiency.

3.4. Boron

Boron (B) is an essential micronutrient for plants, required in trace amounts for their growth, development, and reproduction. Despite its minimal quantitative requirement, boron plays a critical role in cell wall structure, membrane integrity, nutrient transport, and various metabolic processes. Its deficiency or toxicity can have profound effects on plant physiology and productivity, making its proper management crucial for sustainable agriculture.

Boron is a unique micronutrient with specific and irreplaceable functions in plants. Its role is predominantly structural, but it also has regulatory effects on key physiological and biochemical processes.

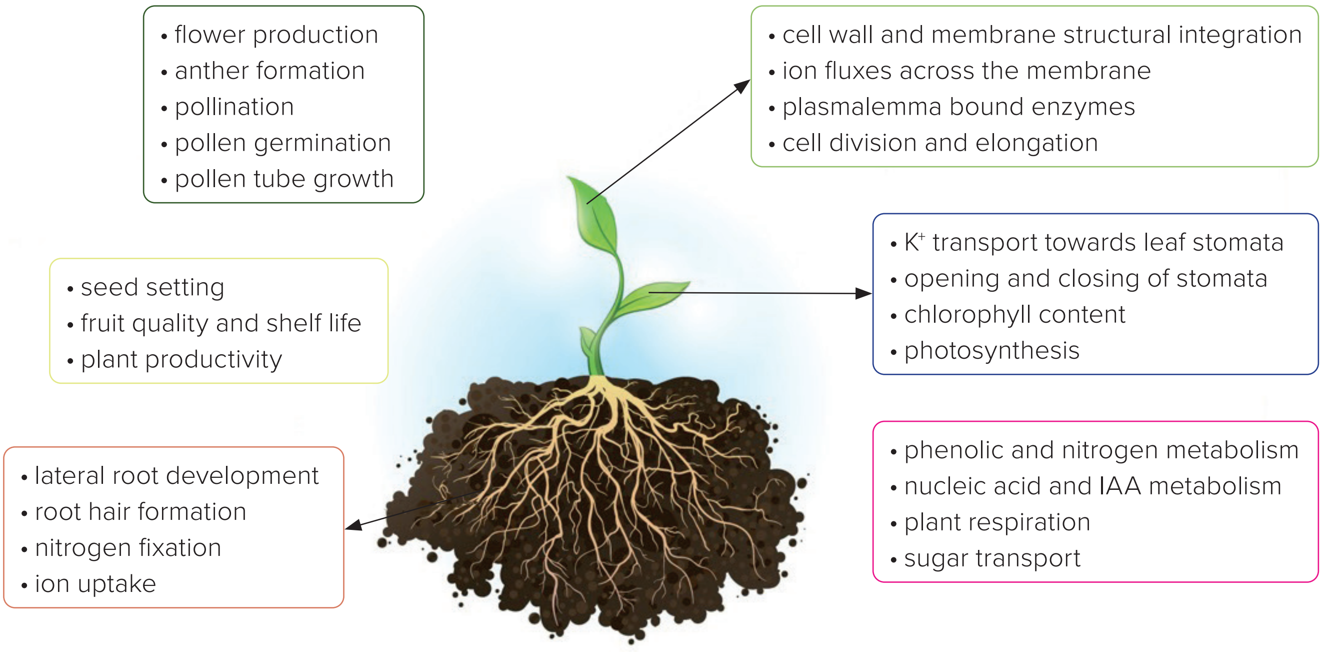

Figure 6: Functions of boron in plants
Source: Shireen, F.; Nawaz, M.A.; Chen, C.; Zhang, Q.; Zheng, Z.; Sohail, H.; Sun, J.; Cao, H.; Huang, Y.; Bie, Z. (2018): *Boron: Functions and Approaches to Enhance Its Availability in Plants for Sustainable Agriculture.* Int. J. Mol. Sci. 19, 1856. https://doi.org/10.3390/ijms19071856
Own editing

Boron is primarily known for its role in maintaining **cell wall integrity**. It forms complexes with pectin molecules, particularly rhamnogalacturonan-II (RG-II), a structural component of the cell wall. Boron cross-links these molecules, providing strength and stability to the cell wall, which is vital for cell division, elongation, and overall plant development. Boron **stabilizes plasma membranes** by interacting with glycoproteins and glycolipids. It helps maintain membrane permeability, fluidity, and selective ion transport. This function is crucial for nutrient and water uptake as well as intracellular signaling. Boron indirectly affects RNA and protein synthesis by **regulating enzyme activities** and energy metabolism. It also plays a role in the synthesis of certain nucleotides and the activation of enzymes involved in protein and carbohydrate metabolism. Boron facilitates the **transport of sugars and carbohydrates** within the plant. It forms complexes with sugars, aiding their translocation from source tissues (e.g., leaves) to sink tissues (e.g., roots, fruits, and seeds). This role is vital for energy distribution and storage. Boron is indispensable for **flowering**, pollen germination, and seed set. It ensures proper pollen tube growth and fertilization, directly impacting fruit and seed development (Figure 6).

Plants absorb boron from the soil solution mainly as boric acid (H_3BO_3). The uptake and transport of boron depend on its availability in the soil, environmental factors, and the plant's needs.

- Passive Uptake: Boric acid, an uncharged molecule, diffuses passively into root cells, driven by the flow of water during transpiration.
- Active Uptake: In boron-deficient conditions, specialized transporters like BOR1 (a boron exporter) and NIPs (nodulin 26-like intrinsic proteins) enhance boron absorption.

Boron is primarily transported through the xylem as boric acid, guided by transpiration. In some plants, such as fruit trees, boron is mobile in the phloem, allowing redistribution to fruits and seeds.

Boron **deficiency** is one of the most widespread micronutrient disorders in plants, particularly in sandy soils, regions with low organic matter, or areas with excessive rainfall. Boron deficiency leads to stunted growth due to impaired cell division and elongation. The growth of meristematic tissues, such as root tips and shoot apices, is severely affected. Leaves of boron-deficient plants often exhibit curling, thickening, or chlorosis. Younger leaves are more affected, as boron is not readily redistributed in most plant species. The most pronounced effects of boron deficiency are observed in reproductive structures. Boron deficiency causes incomplete flower formation or abortion. Impaired pollen germination and pollen tube growth lead to poor fertilization and low fruit set. Roots become short, thickened, and brittle under boron deficiency, reducing their ability to absorb water and nutrients.

Excess boron in the soil can be toxic to plants, leading to physiological and structural damage.

Boron **toxicity** typically manifests as necrotic spots or scorching on the margins of older leaves, progressing towards the center. Excess boron disrupts cell division and elongation, resulting in reduced plant growth and vigor. High boron concentrations interfere with the uptake and utilization of other essential nutrients, such as potassium and magnesium.

Boron plays an important role in enhancing plant **resilience** to various abiotic and biotic stresses. Boron stabilizes cell membranes and maintains their functionality under water-deficit conditions, reducing oxidative damage. Boron strengthens cell walls, making them more resistant to pathogen invasion. It also promotes the synthesis of phenolic compounds and lignin, which act as natural defenses. Boron interacts with heavy metals, mitigating their toxicity by influencing their uptake and compartmentalization. It also has a significant impact on crop productivity and quality. Adequate boron nutrition ensures proper flowering, fruit set, and seed production. Boron enhances fruit size, sugar content, and storage life in crops like apples, grapes, and tomatoes. In crops like cotton, boron improves fiber strength and quality.

To address boron-related issues in **agriculture**, various strategies can be employed. Boron can be supplied through fertilizers such as borax (sodium tetraborate), boric acid, or boron-enriched compost. Regular testing of boron levels ensures optimal application and prevents deficiencies or toxicities. In boron-toxic soils, leaching excess boron with irrigation water can reduce its availability to plants. Foliar sprays of boron provide an immediate remedy for deficiency symptoms, especially during critical growth stages such as flowering and fruiting.

Breeding crops with enhanced boron uptake and utilization efficiency is a sustainable solution. Overexpression of boron transporter genes improves boron acquisition and redistribution in plants. The use of boron-solubilizing microorganisms can enhance boron availability in soils, offering an eco-friendly alternative to chemical fertilizers. Proper boron management contributes to sustainable farming practices. Optimizing boron nutrition ensures higher yields and better quality. Efficient boron use reduces the risk of leaching and contamination of water bodies. Minimizing deficiency-related yield losses and optimizing fertilizer use improve farm profitability. Advancements in boron research aim to improve its management and utilization in agriculture. Nano-boron fertilizers provide targeted delivery, improving uptake efficiency and reducing environmental impact. Understanding the role of boron-solubilizing bacteria offers insights into natural solutions for boron deficiencies. Genomics, proteomics, and metabolomics are being used to study boron transport, signaling, and its role in stress adaptation.

3.5. Molybdenum

Molybdenum (Mo) is an essential micronutrient required in trace amounts by plants, but its importance in plant physiology cannot be overstated. As a key component of various enzymes, molybdenum facilitates vital biochemical reactions involved in nitrogen metabolism, sulfur metabolism, and the detoxification of reactive oxygen species. Molybdenum deficiency, though rare, can have profound effects on plant growth, development, and productivity, especially in specific soil types.

Molybdenum primarily functions as a cofactor for molybdoenzymes, which catalyze essential biochemical reactions. Its physiological roles include nitrogen metabolism, sulfur metabolism, and antioxidant defense, all of which are critical for plant growth and development.

3.5.1. Molybdenum in Nitrogen Metabolism

The most critical role of molybdenum in plants is its involvement in nitrogen assimilation:

- Nitrate Reductase Activity: Molybdenum is a cofactor for nitrate reductase, an enzyme that reduces nitrate (NO_3^-) to nitrite (NO_2^-) during nitrogen assimilation. This step is vital for converting inorganic nitrogen into amino acids and proteins.
- Nitrogen Fixation: In legumes and other nitrogen-fixing plants, molybdenum is a cofactor for nitrogenase, the enzyme responsible for reducing atmospheric nitrogen (N_2) to ammonia (NH_3). This process is critical for symbiotic nitrogen fixation in root nodules.

Molybdenum is a cofactor for xanthine dehydrogenase, an enzyme involved in purine metabolism. This process is important for nitrogen recycling and the detoxification of purine metabolites.

3.5.2. Molybdenum in Sulfur Assimilation

Molybdenum is involved in sulfur assimilation through its role as a cofactor for sulfite oxidase, which converts toxic sulfite (SO_3^{2-}) into sulfate (SO_4^{2-}). Sulfate is a precursor for the synthesis of sulfur-containing amino acids like cysteine and methionine. Molybdenum is a cofactor for xanthine dehydrogenase, an enzyme involved in purine metabolism. This process is important for nitrogen recycling and the detoxification of purine metabolites.

Molybdenum indirectly contributes to the detoxification of reactive oxygen species (ROS) by facilitating proper nitrogen and sulfur metabolism. Imbalances in these pathways can lead to the accumulation of ROS, causing oxidative stress.

Plants **absorb** molybdenum as molybdate ions (MoO_4^{2-}) from the soil. Its uptake and transport are influenced by soil conditions, plant species, and physiological needs. Specific molybdate transporters, such as MOT1 (Molybdate Transporter 1), mediate the uptake of molybdate ions into root cells (active transport). Molybdenum availability is highly dependent on soil pH. Acidic soils reduce molybdenum availability, while alkaline soils increase its solubility. After uptake, molybdenum is transported through the xylem to shoots and leaves, where it is incorporated into molybdoenzymes. It may also be redistributed via the phloem to actively growing tissues and reproductive organs.

Molybdenum is **stored** in vacuoles and organelles such as chloroplasts and mitochondria, where it is used in enzymatic reactions. It is incorporated into a cofactor called molybdopterin, which enables its integration into molybdoenzymes.

Although plants require very small amounts of molybdenum, its deficiency can have severe effects, particularly in acidic or leached soils. Molybdenum **deficiency** often mimics nitrogen deficiency due to its role in nitrate reduction. Yellowing of leaves, particularly in older leaves, due to impaired chlorophyll synthesis. Reduced nitrogen assimilation leads to poor growth and biomass production. In legumes, molybdenum deficiency inhibits nitrogen fixation, resulting in fewer and smaller root nodules. A characteristic symptom of molybdenum deficiency in cruciferous plants (e.g., cauliflower) is whiptail, where leaves become deformed, narrow, and strap-like. Impaired nitrogen metabolism accelerates leaf senescence and reduces the lifespan of affected plants.

Molybdenum **toxicity** is relatively rare but can occur in alkaline soils with excessive molybdenum concentrations. High molybdenum levels interfere with iron metabolism, causing interveinal chlorosis. Excess molybdenum can antagonize the uptake of other nutrients like copper, leading to secondary deficiencies.

Molybdenum plays a role in enhancing plant **tolerance** to various abiotic and biotic stresses. By maintaining nitrogen and sulfur metabolism, molybdenum helps plants cope with osmotic stress and maintain cellular homeostasis under drought or saline conditions. Molybdenum aids in the synthesis of defense-related compounds, such as phytoalexins, which protect plants against pathogens. Molybdenum contributes to the detoxification of heavy metals by regulating redox reactions and maintaining antioxidant defense systems.

To ensure adequate molybdenum availability for plants, several strategies can be employed. Liming acidic soils increases pH, improving molybdenum availability. Application of sodium molybdate or ammonium molybdate can correct deficiencies in deficient soils. Adding compost or organic matter enhances molybdenum retention and availability. Foliar sprays of molybdenum are an effective way to address deficiency symptoms quickly, particularly during critical growth stages.

Breeding crops with enhanced molybdenum uptake and utilization efficiency is a sustainable approach to managing deficiencies. Manipulating genes involved in molybdate transport and metabolism can improve molybdenum efficiency in plants. The use of molybdenum-solubilizing microorganisms can enhance molybdenum availability in the rhizosphere, promoting sustainable nutrient management.

Molybdenum management is integral to **sustainable farming** practices. By supporting nitrogen assimilation and fixation, molybdenum improves crop productivity and reduces the need for synthetic fertilizers. Efficient molybdenum use minimizes nutrient leaching and associated environmental pollution. Adequate molybdenum nutrition enhances the nutritional value of crops, benefiting human and animal health. Recent advancements in molybdenum research aim to improve its management and utilization. Identifying genes involved in molybdenum transport and metabolism offers insights into improving its efficiency. Nano-molybdenum fertilizers provide targeted delivery, enhancing uptake and reducing environmental impact. Understanding the role of rhizosphere microorganisms in molybdenum cycling can inform the development of biofertilizers.

3.6. Copper

Copper (Cu) is an essential micronutrient required for plant growth, development, and physiological processes. Despite its relatively low concentration in plants, copper plays a critical role as a cofactor for enzymes, a regulator of metabolic pathways, and a participant in electron transport chains. The dual nature of copper, being both essential and potentially toxic, indicates the importance of maintaining its homeostasis in plants.

Copper is indispensable for various physiological and biochemical functions in plants. Its primary roles include participation in redox reactions, activation of enzymes, maintenance of cell wall structure, and facilitation of photosynthesis.

Copper is a **cofactor** for numerous enzymes involved in essential metabolic pathways. Plays a critical role in mitochondrial electron transport and energy production during respiration.

Superoxide Dismutase (Cu/Zn-SOD): Detoxifies reactive oxygen species (ROS) by converting superoxide radicals (O_2^-) into hydrogen peroxide (H_2O_2), protecting cells from oxidative damage. Involved in lignin synthesis and plant defense mechanisms. Regulates the redox state of ascorbate, a vital antioxidant, influencing stress tolerance and growth. Copper plays a key role in lignin synthesis, which strengthens plant cell walls and aids in structural support and defense. It also helps regulate the redox state of ascorbate, a crucial antioxidant that enhances stress tolerance and promotes healthy plant growth.

Copper is a key component of plastocyanin, a protein involved in the **photosynthetic electron transport chain**. Plastocyanin transfers electrons from cytochrome b6f to Photosystem I, facilitating light-driven energy conversion. Copper is essential for the activity of enzymes such as laccases, which catalyze the polymerization of lignin. Lignin provides structural integrity and resistance to biotic and abiotic stresses. Copper influences ethylene synthesis by acting as a cofactor for 1-aminocyclopropane-1-carboxylic acid oxidase (ACC oxidase), an enzyme involved in the final step of ethylene biosynthesis. Ethylene regulates growth, development, and stress responses.

Copper is **absorbed** by plant roots as Cu^{2+} or, less commonly, Cu^{+} ions. Its **uptake and transport** are tightly regulated to meet plant demands while preventing toxicity. Copper is taken up from the rhizosphere through high-affinity copper transporters, such as those in the COPT (Copper Transporter) family. These transporters mediate the active transport of copper ions into root cells. Copper availability decreases in alkaline soils, where it forms insoluble compounds. Copper binds to organic matter, influencing its bioavailability. High concentrations of other cations, such as zinc or iron, can inhibit copper uptake. After uptake, copper is complexed with organic ligands, such as amino acids or peptides, and transported through the xylem to aerial parts of the plant. Copper is then redistributed via the phloem to growing tissues, seeds, and reproductive organs. Within cells, copper is delivered to organelles, such as chloroplasts and mitochondria, where it is incorporated into copper-dependent proteins. Specialized copper chaperones, such as ATX1 and CCS, ensure the safe delivery of copper to target enzymes and prevent free copper accumulation.

Copper **deficiency** can severely impair plant growth and productivity. The symptoms vary depending on the plant species, developmental stage, and severity of the deficiency. Copper deficiency disrupts photosynthesis, leading to interveinal chlorosis (yellowing of leaves while veins remain green). This is due to impaired plastocyanin activity. Plants exhibit reduced growth and biomass due to insufficient energy production and disrupted metabolic pathways.

In severe cases, leaf tips and margins may develop necrotic spots due to oxidative stress and cellular damage. Copper deficiency affects reproductive development, causing poor pollen viability, incomplete flower formation, and low seed set. Deficiency impairs lignin synthesis, leading to weak stems and increased susceptibility to lodging and pathogen invasion.

Excessive copper can be **toxic** to plants, causing physiological and biochemical disruptions.

High copper concentrations damage chloroplasts and other cellular components, leading to leaf discoloration and tissue death. Toxic levels of copper impair root elongation and branching, reducing nutrient and water uptake. Copper toxicity inhibits the activity of essential enzymes by displacing other metal cofactors or causing oxidative damage.

Copper toxicity generates ROS through Fenton-like reactions, leading to oxidative stress. Additionally, excess copper disrupts nutrient homeostasis by competing with other essential cations, such as zinc and iron.

Copper plays a significant role in enhancing plant **resilience** to environmental stresses. Copper-dependent enzymes like Cu/Zn-SOD protect plants from oxidative damage caused by drought, salinity, and heavy metal stress. Copper contributes to the synthesis of lignin and other secondary metabolites that fortify cell walls, providing a barrier against pathogen invasion. Copper also activates defense-related enzymes and phytoalexins. Copper influences the synthesis of stress-responsive proteins and antioxidants, improving plant tolerance to extreme temperatures.

Maintaining adequate copper levels in plants is essential for optimal growth and productivity. Strategies to manage copper nutrition include soil amendments, foliar applications, and breeding approaches. Copper sulfate and chelated copper are commonly used to correct deficiencies. Regular testing ensures that copper levels are within the optimal range, preventing deficiency or toxicity. Adjusting soil pH to a slightly acidic range increases copper availability.

Foliar sprays provide a quick and efficient method to address copper deficiencies, especially during critical growth stages. Breeding plants with enhanced copper uptake and utilization efficiency is a sustainable approach to managing copper nutrition. Manipulating genes involved in copper transport and homeostasis can improve copper efficiency and stress tolerance. The use of copper-solubilizing microorganisms can enhance copper availability in the rhizosphere, reducing reliance on chemical fertilizers.

Copper plays a crucial role in **sustainable farming** systems by improving crop productivity and quality while minimizing environmental impacts. Adequate copper nutrition supports photosynthesis, enzyme activity, and reproductive development, leading to improved yields.

Copper influences the synthesis of proteins, antioxidants, and secondary metabolites that enhance crop quality. Using copper-efficient plants and biofertilizers reduces the need for excessive fertilizer applications, promoting environmental sustainability. Recent advancements in copper research aim to improve its management and utilization in agriculture. Identifying and characterizing genes involved in copper uptake, transport, and homeostasis provides insights into improving copper efficiency. Nano-copper fertilizers offer targeted delivery and enhanced bioavailability, reducing environmental risks. Studying the role of rhizosphere microorganisms in copper cycling can inform the development of natural solutions for managing copper deficiencies.

4.
The Effect of Toxic Elements and Heavy Metals Found in Industrial By-Products and Waste on Plants

Industrialization, while driving economic growth, has led to the generation of vast quantities of by-products and waste. These materials often contain toxic elements and heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr). When these substances are introduced into the environment, they pose significant risks to ecosystems, particularly plants, which are vital components of the food chain and natural systems. The accumulation of toxic elements in soils impacts plant growth, health, and productivity. This chapter summarizes the sources, mechanisms of toxicity, effects on plants, and strategies to mitigate these challenges.

By-products such as tailings and slag are often rich in heavy metals like arsenic, lead, and mercury. These elements leach into soils, contaminating agricultural land.

Wastes from chemical plants, including dyes, pigments, and batteries, contain cadmium, chromium, and other harmful elements.

Coal combustion generates fly ash and bottom ash, which contain elements such as selenium (an essential element that is toxic to aquatic life when accumulated in high concentrations), vanadium, and arsenic, Improper disposal of e-waste releases heavy metals such as lead, cadmium, and mercury into the environment.

Industrial effluents used for irrigation often carry metals that accumulate in soils over time.

Toxic elements and heavy metals affect plants through several mechanisms (Figure 25):

- Heavy metals in soil solution are absorbed by plant roots through passive or active transport. They accumulate in root tissues and are often transported to shoots.
- Heavy metals disrupt cellular homeostasis by binding to enzymes and proteins, inhibiting their function. They replace essential metal ions like calcium and magnesium in physiological processes.
- Heavy metals also can induce oxidative stress. Plants respond to oxidative stress by increasing the production of antioxidant enzymes such as superoxide dismutase (SOD), ascorbate peroxidase (APX), or guaiacol peroxidase (POD). In addition, toxic metals induce the generation of reactive oxygen species (ROS), which damage lipids, proteins, and nucleic acids, impairing cellular integrity.

- Heavy metals compete with essential nutrients for uptake, causing deficiencies in vital elements like potassium, zinc, and iron.
- Heavy metals, especially lead and cadmium, inhibit cell division in root meristems, reducing root length and mass.
- Exposure leads to thicker and darker roots with reduced branching.
- Metals like mercury and cadmium disrupt chlorophyll biosynthesis and promote its degradation.
- Heavy metals interfere with photosystem II, reducing photosynthetic efficiency and energy production.
- Arsenic and chromium block the uptake of essential nutrients like phosphorus and potassium, leading to deficiencies.
- Plants exposed to heavy metals exhibit reduced biomass accumulation due to inhibited cell division and elongation.
- Toxic metals impair flowering, pollination, and seed development, reducing crop yields and quality.
- Visible symptoms include leaf chlorosis, necrosis, wilting, and discoloration. In severe cases, entire plant death occurs.

In regions with industrial runoff, cadmium accumulates in rice grains, posing health risks to consumers. The affected plants show stunted growth and lower yields.

Lead contamination in urban soils inhibits root and shoot growth in vegetables like spinach and lettuce. The plants often show chlorosis and wilting.

Strategies for mitigating metal toxicity

Arsenic-contaminated irrigation water in parts of South Asia has led to its accumulation in crops like wheat and paddy, causing leaf necrosis and reduced productivity. Heavy metals alter soil microbial communities and reduce soil fertility, making the land unsuitable for agriculture. Toxic metals accumulate in plant tissues and enter the food chain, affecting animals and humans. Metal toxicity reduces plant diversity by favoring metal-tolerant species over others.

Certain plants, such as sunflowers, Indian mustard, and vetiver grass, can extract heavy metals from contaminated soils.

Adding lime neutralizes soil pH, reducing metal solubility.

Compost and biochar bind metals, limiting their bioavailability to plants.

Growing metal-tolerant crops or varieties bred for heavy metal resistance in contaminated areas promote plant production under the circumstances.

Avoiding the use of contaminated water for irrigation (using treated water or rainwater harvesting systems) prevent soil contamination.

Implementing stricter controls on industrial waste disposal and promote environmentally sound recycling of industrial by-products can prevent toxicity.

Developing plants with enhanced detoxification mechanisms through genetic engineering or traditional breeding methods can promote plant health.

Using metal-resistant microbes to immobilize or degrade toxic elements in soils can promote soil health.

Employing nanotechnology for precise remediation of contaminated soils and effective metal recovery from waste also safeguards soil health.

It is also key to encourage industries to adopt circular economy principles, transforming by-products into safe, value-added resources.

Toxic elements and heavy metals in industrial by-products and waste pose significant challenges to plant health and productivity. By disrupting physiological processes, inducing oxidative stress, and impairing growth, these substances threaten agricultural sustainability and food security. However, through innovative strategies such as phytoremediation, soil amendments, and crop breeding, the adverse effects of heavy metal contamination can be mitigated. To secure the future of agriculture, a collaborative approach involving industries, researchers, and policymakers is essential. Transforming industrial waste management from an environmental liability to a sustainable resource model will ensure the resilience of ecosystems and the well-being of all living organisms.

4.1. Characteristics of aluminum toxicity and its effects on plants

Aluminum (Al) is the third most abundant element in the Earth's crust, often present in soils in forms that are harmless to plants. However, under acidic soil conditions (pH < 5.5), aluminum solubilizes into its toxic ionic form, Al^{3+}. This form interferes with root growth, nutrient uptake, and overall plant health, severely impacting crop productivity. Aluminum toxicity is a critical issue in agriculture, particularly in tropical and subtropical regions where acidic soils dominate.

Aluminum toxicity is a global concern, affecting over 50% of the world's arable land. It is especially severe in regions with naturally acidic soils, such as parts of South America, Africa, and Southeast Asia. Aluminum toxicity primarily occurs in acidic soils where pH levels drop below 5.5. In these conditions, aluminum bound in insoluble forms such as aluminosilicates or oxides becomes soluble, releasing Al^{3+} ions into the soil solution. Because of their high valence, these ions are highly reactive and are capable of interfering with various cellular processes in plants.

The presence of Al as precipitates or as conjugated organic and inorganic molecular ions depends on the pH of the soil. The behavior of Al in the environment is influenced by its coordination chemistry. Al's lower ionic radius and higher ionic charge cause its reactions in soil to differ from those of other soluble metals. In actuality, the pH and the chemical environment of the soil solution mostly determine the concentration and speciation of Al. As the pH increases above 4.0, Al^{3+} forms mono-nuclear species and soluble complexes with inorganic ligands like $(SO_4)^{2-}$, (OH)-, phosphates, silicates, and F- and also with many organic compounds. Molecular aluminum (mononuclear) exists as hydroxyl aluminum: $Al/Al(H_2O)_6^{3+}$, $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_3$ and $Al(OH)_4^-$. Trivalent aluminum (Al^{3+}) is the most prevailing form and has the highest impact on plant growth at pH < 5. At pH 5–6.2, the dominant species are $Al(OH)^{2+}$ and $Al(OH)_2^+$, which are toxic to dicotyledonous plants but not as toxic as Al^{3+}.

The highest mobility of Al occurs between pH 4.0 and 4.5.

Aluminum toxicity manifests quickly in susceptible plants, often within hours or days of exposure. The first symptoms typically appear in the **root system**, making it a critical indicator of aluminum stress. The primary site of aluminum toxicity is the root apex, particularly the elongation zone and root cap. These regions are crucial for root growth and nutrient absorption and are especially vulnerable to Al^{3+} interference.

Aluminum ions disrupt cell division and elongation in the root tip, leading to stunted root growth. Affected roots often appear thicker and darker, with reduced branching and increased brittleness.

In a short-term, control experiment with 25 Pinto bean cultivars, the Al-induced primary root inhibition varied between 15.25% and 72.39% 4 h after 20 µM Al treatment. Root growth inhibition was higher 8 h after Al treatment, increasing from 36.67% to 86.00%, compared to the values 4 h after Al treatment. The root length inhibition was between 7.88% and 95.00% at 48 h and between 35.43% and 96.15% at 72 h after Al treatment (Table 1).

Table 1: The root length inhibition percentage of 25 common bean cultivars 4, 8, 24, 48, and 72 h after $AlCl_3$ treatment, relative to non-stressed controls.

Cultivars	Al-induced root length inhibition as a percentage (%)				
	0–4 h	4–8 h	8–24 h	24–48 h	48–72 h
AC Island	30	58	19	31	56
Apache	55	74	81	89	91
Arapaho	49	48	−6	8	35
Aztec	62	46	82	95	97
Bill Z	30	36	7	22	51
Buckskin	72	79	84	85	77
Burke	15	76	78	87	96
Croissant	46	77	68	86	75
Fargo	40	80	83	74	81
Flint	65	69	86	81	82
Grand Mesa	54	46	26	31	39
Kimberly	67	85	90	93	96
Kodiak	39	78	68	78	71

Cultivars	Al-induced root length inhibition as a percentage (%)				
	0–4 h	4–8 h	8–24 h	24–48 h	48–72 h
La Paz	37	71	73	75	79
Max	57	68	77	84	82
Montrose	53	77	80	92	88
Ouray	24	55	21	19	48
Poncho	39	79	9	94	92
Pinto	42	57	85	85	76
Quincy	51	7	76	75	78
Santa Fe	56	83	76	79	74
Sierra	62	84	80	90	87
TARS-09	56	77	80	42	89
Topaz	35	86	77	94	90
Windbreaker	49	85	82	78	86

Values represent means (n = 12)

Source: Own data

The effects of Al in plants are as follows:

- It competes with essential cations like Ca^{2+} and Mg^{2+}, reducing their uptake and transport within the plant. Al^{3+} binds to phosphorus in the soil and within plant cells, rendering it unavailable for critical processes such as energy transfer and photosynthesis.
- Aluminum induces the production of reactive oxygen species (ROS), causing damage to lipids, proteins, and DNA. This oxidative stress compromises cellular integrity and function.
- Al^{3+} destabilizes cell membranes by interacting with phospholipids and proteins, leading to increased permeability and ion leakage.
- Aluminum toxicity reduces chlorophyll content, impairing photosynthetic efficiency.
- Limited nutrient availability and root dysfunction lower the plant's ability to assimilate carbon dioxide, resulting in poor growth and biomass production.
- Plants exposed to aluminum toxicity exhibit reduced overall growth, lower reproductive success, and diminished crop yields.

Plants have evolved mechanisms such as the following to exclude aluminum from sensitive tissues:

- Roots secrete organic acids such as citrate, malate, and oxalate, which chelate Al^{3+} ions in the rhizosphere, reducing their toxicity.
- Specific transporters like ALMT (Aluminum-Activated Malate Transporter) and MATE (Multidrug and Toxic Compound Extrusion) play crucial roles in organic acid exudation.

- Plants can immobilize aluminum within cell walls or vacuoles, preventing it from interacting with vital cellular components.
- Genes involved in antioxidant defense, membrane repair, and signal transduction are upregulated under aluminum stress, aiding in damage mitigation.

What can we do to mitigate the aluminum stress?

Applying lime raises soil pH, precipitating Al^{3+} ions into non-toxic forms. Lime primarily consists of calcium carbonate ($CaCO_3$) while dolomite lime contains magnesium carbonate ($MgCO_3$) and calcium carbonate as well. In addition, Dolomite is primarily composed of calcium magnesium carbonate, represented by the chemical formula $CaMg(CO_3)_2$, meaning it is made up of equal parts calcium and magnesium combined with carbonate ions; essentially, it's a mixture of calcium carbonate and magnesium carbonate. When lime applied to acidic soils, it dissolves and releases carbonate ions (CO_3^{2-}) or hydroxide ions (OH^-). These ions react with the hydrogen ions (H^+) in the soil solution, forming water (H_2O) and carbon dioxide (CO_2). The carbonate or hydroxide ions react with Al^{3+}, forming solid aluminum hydroxide ($Al(OH)_3$) or other insoluble aluminum compounds, preventing its toxic effects on plant roots. As the concentration of hydrogen ions (H^+) decreases due to the reaction with lime, the soil pH increases (becomes less acidic. This promotes better root development, nutrient uptake, and water absorption. In acidic Brazilian soils, liming increased maize yields by 40% due to improved root growth and phosphorus availability. Combining lime with organic matter further enhanced soil fertility. In acidic soils used for tea cultivation, the lime application raised pH and reduced leaf scorch caused by aluminum toxicity, resulting in higher tea quality and yield.

Smallholder farmers reported improved cassava and maize yields after adopting phased lime applications, supported by government subsidies for lime procurement.

Organic matter improves soil structure and enhances the chelation of aluminum through increased organic acid production.

Biochar can adsorb Al^{3+} ions and improve soil fertility. Biochar has a highly porous structure and a large specific surface area, providing numerous adsorption sites for Al^{3+} ions. Carboxyl, hydroxyl, and other oxygen-containing groups on the biochar surface interact with Al^{3+} through cation exchange and complexation. Biochar's high cation exchange capacity enables it to adsorb and immobilize Al^{3+} ions, reducing their bioavailability. In addition, biochar typically has an alkaline pH due to its ash content, which can neutralize soil acidity. This raises the soil pH and converts Al^{3+} into non-toxic hydroxide forms, such as aluminum hydroxide ($Al(OH)_3$). Biochar derived from eucalyptus residues was used to rehabilitate degraded acidic soils, improving soil fertility and promoting the growth of native tree species. Field trials demonstrated that biochar reduced aluminum saturation in acidic soils and enhanced maize yields by 25%, particularly when combined with compost. In acidic tea-growing regions, biochar application reduced Al^{3+} toxicity by 40% and improved soil pH and organic matter, resulting in higher tea yields and quality.

Foliar sprays of essential nutrients bypass soil-aluminum interactions and deliver nutrients directly to plants. In acidic soils, aluminum ions compete with essential nutrients, such as phosphorus, magnesium, and calcium, reducing their availability to plants. Foliar sprays eliminate this competition by delivering nutrients directly to the leaves. Nutrient deficiencies caused by aluminum toxicity can be quickly addressed through foliar applications, as uptake is faster compared to soil amendments. This is particularly useful during critical growth stages such as flowering and fruiting. In acidic paddy fields of Southeast Asia, foliar sprays of potassium phosphate improved grain yield and quality, compensating for phosphorus unavailability due to aluminum toxicity. Calcium and magnesium sprays were used to mitigate leaf scorch and fruit drop in aluminum-affected citrus orchards, leading to a 25% increase in fruit production. Combining foliar sprays of zinc and boron with lime application enhanced maize growth in aluminum-toxic soils, demonstrating a synergistic approach. Integrating foliar sprays into precision agriculture systems enables site-specific nutrient delivery, minimizing waste and maximizing efficiency.

Rotation with aluminum-tolerant crops or legumes that enhance soil fertility can reduce toxicity over time. Aluminum-tolerant crops are capable of growing in soils with high levels of soluble aluminum. These crops possess physiological and biochemical mechanisms to cope with Al stress. Many aluminum-tolerant crops exude organic acids like citric and malic acid from their roots, chelating Al^{3+} ions and reducing their bioavailability.

Aluminum-tolerant crops are Sorghum *(Sorghum bicolor):* Known for its ability to tolerate acidic soils and aluminum stress, sorghum is a staple in many regions with marginal lands.

Barley *(Hordeum vulgare):* Exhibits high aluminum tolerance, making it suitable for acidic soils in temperate regions. Cassava *(Manihot esculenta):* Thrives in low-fertility soils with high aluminum content, providing food security in tropical areas.

Soybean *(Glycine max):* Enhances soil nitrogen and performs well in moderately acidic soils.

Cowpea *(Vigna unguiculata):* A versatile legume that improves nitrogen content and soil organic matter. Lupins *(Lupinus spp.):* Particularly effective in acidic soils, lupins exude organic acids that chelate aluminum and solubilize phosphorus.

Legume rotations replenish essential nutrients, particularly nitrogen, reducing the need for synthetic fertilizers. This contributes to sustainable soil management and long-term productivity.

Mulches reduce soil acidification by buffering pH and promoting microbial activity.

Addressing aluminum toxicity requires a multi-pronged approach involving agronomy, soil science, and biotechnology.

Aluminum-tolerant plants exude organic acids such as malate, citrate, and oxalate from their roots, which chelate Al^{3+} ions and render them non-toxic. **Genes** such as ALMT1 (Aluminum-Activated Malate Transporter 1) and MATE (Multidrug and Toxic Compound Extrusion) are key regulators of this process. Editing promoters of genes like ALMT1 and MATE to enhance their expression leads to increased organic acid exudation. Silencing genes that suppress aluminum tolerance pathways enhances the plant's natural defenses.

Utilize **genomic tools** like CRISPR/Cas9 to develop aluminum-tolerant crops with improved efficiency. CRISPR/Cas9 is a precise and efficient genome-editing tool that enables targeted modifications in the plant genome. Combining CRISPR/Cas9 with traditional breeding methods accelerates the development of aluminum-tolerant crop varieties. CRISPR/Cas9 was used to enhance the expression of OsFRDL4 in rice, a gene involved in citrate exudation, improving aluminum tolerance and root growth in acidic soils. Knockout of TaSTOP1, a repressor gene, increased the expression of downstream aluminum-tolerance genes in wheat, significantly improving malate and citrate exudation. Editing genes responsible for antioxidant enzyme production improved the plant's ability to withstand aluminum-induced oxidative stress in soybean experiments. In maize, the overexpression of ZmMATE1, a gene linked to citrate transport, enhanced aluminum detoxification and root elongation in acidic soils. Unlike traditional breeding, which can take years, CRISPR/Cas9 accelerates the development of improved crop varieties.

Exploring the role of **aluminum-resistant microbes** that can enhance organic acid production and chelation in the rhizosphere is important. By mitigating Al toxicity, aluminum-resistant microbes enable better root elongation and branching, increasing the root surface area for water and nutrient absorption. Organic acids secreted by microbes solubilize essential nutrients such as phosphorus, iron, and manganese, which are often immobilized in acidic soils. In addition to reducing Al toxicity, these microbes promote plant growth through mechanisms such as nitrogen fixation, production of growth-promoting hormones, and disease suppression. Continuous organic acid production by microbes helps neutralize soil acidity over time, creating a more favorable environment for both plants and beneficial soil organisms. Aluminum-resistant microbes can be formulated into bioinoculants for direct application to seeds, roots, or soil. These bioinoculants improve crop productivity in acidic soils without the need for costly chemical amendments. Microbial inoculants can be paired with aluminum-tolerant crop varieties to maximize productivity in challenging environments. Such synergies address soil and crop-specific constraints more effectively. For example, *Pseudomonas fluorescens* is known for producing citric acid and malic acid, significantly reducing Al^{3+} toxicity in maize and wheat. Field experiments showed improved root architecture and a 20–30% increase in crop yield in acidic soils. In addition, certain Rhizobium strains tolerated aluminum and support nitrogen fixation in legumes, improving soil fertility and plant growth under aluminum stress.

The use of aluminum-resistant microbes reduces dependence on synthetic fertilizers and lime, decreasing the environmental footprint of agriculture. Rehabilitating acidic and aluminum-toxic soils with microbial interventions enables the cultivation of previously unproductive lands, supporting global food security. Improved plant growth in treated soils contributes to higher biomass production and carbon storage, mitigating climate change.

Nanotechnology offers a transformative solution by enabling the development of **nanoparticles** (NPs) designed for the precise delivery of liming agents or nutrients to affected soils. These nanoparticles can enhance the efficiency of soil amendments, reduce environmental impact, and support sustainable agriculture. This following section explores the principles of nanoparticle design, mechanisms of delivery, potential benefits, challenges, and future applications in combating soil acidity and aluminum toxicity. Due to their high reactivity and controlled release properties, nanoparticles require smaller quantities to achieve the same or superior effects compared to conventional methods. However, the synthesis of nanoparticles, especially at large scales, can be expensive, potentially limiting their accessibility for smallholder farmers. The long-term impact of nanoparticles on soil ecosystems and human health is not yet fully understood, requiring thorough risk assessments. The adoption of nanotechnology in agriculture is hindered by unclear regulations and a lack of standardized guidelines for nanoparticle use. In addition, addressing aluminum toxicity in diverse agro-ecosystems requires a combination of strategies, including soil amendments, aluminum-tolerant crops, and sustainable practices, alongside overcoming technical challenges such as the uniform application of nanoparticles, which necessitates the development of specialized delivery systems like sprays or seed coatings.

In summary, aluminum toxicity poses a significant threat to agricultural productivity, particularly in acidic soils where Al^{3+} ions disrupt root growth, nutrient uptake, and overall plant health. Its impact is felt globally, affecting food security and soil sustainability. However, through innovative strategies such as soil amendments, breeding aluminum-tolerant crops, and improving agronomic practices, the adverse effects of aluminum toxicity can be mitigated. As research advances and new technologies emerge, a comprehensive approach integrating soil science, plant biology, and sustainable farming will be key to overcoming the challenges posed by aluminum toxicity and ensuring resilient agricultural systems.

4.2. Characteristics of Cadmium Toxicity and Its Effects on Plants

Cadmium (Cd) contamination in soil has emerged as a critical environmental issue, primarily driven by anthropogenic activities such as industrial waste disposal, mining, and the excessive use of phosphate fertilizers. This heavy metal, known for its high toxicity even at low concentrations, poses significant risks to soil health and agricultural productivity. Central to soil health are its microbial communities, which perform essential functions like nutrient cycling, organic matter decomposition, and the maintenance of soil structure. However, the presence of cadmium in soil disrupts these microbial communities, impairing their functions and leading to a decline in soil fertility. Although not essential for plant growth, cadmium is readily absorbed by plants, where it interferes with physiological and biochemical processes. The toxic effects of cadmium pose significant challenges to agriculture, as they reduce crop yield and quality while also posing risks to human health throughout the food chain. Cadmium is present in the Earth's crust, often associated with zinc ores. Industrial emissions, mining activities, sewage sludge, and cadmium-containing fertilizers contribute to its accumulation in agricultural soils.

Cadmium is highly soluble in acidic soils, making it readily available for plant uptake. **Cadmium is absorbed by plant roots** via transporters that also facilitate the uptake of essential nutrients like calcium, zinc, and iron (Figure 29). It **accumulates in plant tissues**, with higher concentrations often found in roots compared to shoots and leaves. Even at low concentrations, cadmium can have **toxic effects** on plants. Its toxicity is dose-dependent, with symptoms becoming more severe as cadmium levels increase.

Cadmium toxicity has far-reaching effects on plants, compromising their physiological functions, growth, and productivity. One of the most significant impacts of cadmium is its ability to induce **oxidative stress** in plants. This occurs when cadmium stimulates the production of reactive oxygen species (ROS), such as hydrogen peroxide and superoxide anions. These reactive molecules cause damage to essential cellular components, including lipids, proteins, and DNA, disrupting normal cellular metabolism. Key processes like photosynthesis are particularly affected, as cadmium impairs chloroplast structures and reduces chlorophyll synthesis. Cadmium damages chloroplast structure and function, reducing the efficiency of photosystems and carbon fixation. Plants exposed to cadmium often exhibit chlorosis (yellowing of leaves), reduced photosynthetic efficiency, and compromised energy production.

In addition to oxidative stress, cadmium **interferes with nutrient and water uptake** by plants. It competes with essential minerals like calcium, magnesium, zinc, and iron, inhibiting their absorption and translocation within the plant. This leads to nutritional deficiencies that further impair physiological processes. For instance, iron deficiency due to cadmium interference reduces chlorophyll production, exacerbating photosynthetic inefficiency. Cadmium also disrupts root morphology, reducing root elongation, surface area, and biomass. These changes impair the plant's ability to anchor itself and access water and nutrients, further diminishing overall health.

The cumulative effects of cadmium toxicity result **in stunted growth, reduced biomass**, and significant **yield losses**. Crops like rice, wheat, and maize have demonstrated substantial declines in productivity when grown in cadmium-contaminated soils. For example, rice plants exhibit reduced tillering and grain filling, while maize shows lower germination rates and diminished cob development. Beyond these agronomic concerns, cadmium accumulation in edible plant parts poses severe food safety risks, leading to human health issues such as kidney damage and bone disorders.

Furthermore, cadmium's impact on plants creates a feedback loop with **soil health**. Poor plant growth leads to reduced organic matter inputs, limiting resources for soil microbes and exacerbating soil degradation. As cadmium-contaminated plant residues decay, they perpetuate soil contamination, creating a cycle of declining fertility and productivity that threatens agricultural sustainability.

Cadmium contamination has profound implications for soil fertility, primarily through its adverse effects on soil microbial communities and plant health. As the intricate balance between soil organisms and plant systems deteriorates, the essential processes that sustain soil fertility are disrupted, resulting in long-term degradation. One of the most critical consequences of cadmium contamination is the decline in nutrient availability. Microorganisms in the soil play a central role in nutrient cycling, converting organic matter into bioavailable forms of nitrogen, phosphorus, and potassium that plants can absorb. However, cadmium toxicity reduces microbial biomass and diversity, impairing key processes like nitrogen fixation and phosphorus solubilization. Beneficial microorganisms such as nitrogen-fixing bacteria and phosphate-solubilizing fungi are particularly sensitive to cadmium, leading to nutrient deficiencies in the soil. This directly affects plant growth, further diminishing the soil's capacity to support vegetation.

The structural integrity of the soil is another casualty of cadmium-induced microbial and plant damage. Soil microbes contribute to the formation of soil aggregates, which enhance aeration, water retention, and resistance to erosion. The loss of microbial activity weakens these structures, making the soil more prone to erosion and compaction. Moreover, the deterioration of root systems in cadmium-contaminated soils further exacerbates these issues. Roots help bind soil particles and improve soil porosity, but their impaired growth leaves the soil vulnerable to environmental stresses like heavy rains and droughts.

The combined effects of disrupted nutrient cycling, reduced organic matter inputs, and compromised soil structure culminate in long-term infertility. Once soil fertility is lost, recovery becomes exceedingly difficult, particularly in regions heavily burdened by industrial pollution or intensive agricultural practices. The inability to sustain healthy plant growth perpetuates a cycle of land degradation, reducing arable land availability and threatening food security on a global scale.

The consequences of cadmium contamination extend beyond soil health, as infertile soils lead to reduced agricultural productivity, economic losses, and increased dependence on chemical fertilizers. While these inputs may provide short-term solutions, they often exacerbate the problem by introducing additional contaminants or altering soil chemistry, making sustainable restoration even more challenging.

Mitigating these impacts requires a multi-pronged approach that addresses the root causes of cadmium contamination and restores soil functionality. The next section explores strategies to achieve these goals through remediation, regulation, and sustainable agricultural practices. Mitigating the effects of Cd contamination requires a comprehensive approach combining remediation technologies, regulatory frameworks, and sustainable agricultural practices. These strategies aim to reduce cadmium levels in the soil, restore microbial and plant health, and prevent further contamination.

The transmission of Cd to higher trophic levels of the food chain has made remediation of Cd-contaminated soil an increasingly important issue worldwide. The capacity of cadmium hyperaccumulators to withstand and absorb large concentrations of heavy metals from soils makes them particularly interesting. The capacity of various plant species to hyperaccumulate Cd varies. Since Cd is mobile and has low affinities with soil ligands, it can be readily taken up by roots and transferred to other aerial parts of the plant. The pH, temperature, Cd concentration in media, and even the concentration of elements other than Cd are the parameters that cause plants to remediate Cd. Figure 30 illustrates the phytoremediation process used to remove Cd from soil.

Bioremediation harnesses the natural abilities of microorganisms to detoxify cadmium-contaminated soils. Certain bacteria and fungi can immobilize or transform cadmium into less toxic forms through biosorption, bioaccumulation, or enzymatic reduction. For example, cadmium-resistant bacterial strains like *Pseudomonas* and *Bacillus* have shown promise in remediating contaminated soils.

Phytoremediation, the use of plants to absorb, stabilize, or degrade contaminants, is another effective strategy. Hyperaccumulator plants such as *Brassica juncea* (Indian mustard) and *Thlaspi caerulescens* efficiently take up cadmium from the soil, concentrating it on their biomass. These plants can then be harvested and disposed of safely, gradually reducing cadmium levels in the soil over successive cycles.

Effective **regulations** are critical to preventing further cadmium contamination. Governments can enforce strict limits on cadmium emissions from industries, monitor the cadmium content in fertilizers and sewage sludge, and regulate the disposal of industrial and urban waste. International collaboration to establish and adhere to cadmium standards in agricultural inputs, such as phosphate fertilizers, is also essential to minimize contamination at the source.

Adopting **sustainable farming practices** can help reduce cadmium accumulation in soils. Organic farming, which relies on compost and manure instead of chemical fertilizers, minimizes the introduction of cadmium into agricultural lands. Crop rotation and intercropping can improve soil health and microbial diversity, making the soil more resilient to contamination. Additionally, soil amendments such as biochar, lime, and zeolite can be used to immobilize cadmium, reducing its bioavailability and toxicity to plants and microbes. Raising awareness among farmers, policymakers, and industries about the dangers of cadmium contamination is vital for long-term success. Educational programs can teach sustainable practices and promote the use of safer fertilizers and soil amendments. Continued research into advanced remediation technologies, cadmium-tolerant crop varieties, and microbial inoculants can further enhance our ability to combat contamination.

By combining these strategies, cadmium contamination can be mitigated while simultaneously promoting soil restoration and agricultural sustainability. Collaborative efforts among scientists, policymakers, farmers, and communities will be critical to achieving these goals.

4.3. Characteristics of Lead Toxicity and Its Effect on Plants

Lead (Pb), a heavy metal widely used in industrial applications, is one of the most persistent and harmful environmental pollutants. While naturally present in trace amounts in the Earth's crust, its accumulation in soils has increased significantly due to human activities such as mining, manufacturing, and the use of leaded gasoline and pesticides. Lead contamination in agricultural soils poses serious challenges to plant health and productivity. Lead toxicity affects plants through various mechanisms, disrupting physiological processes and reducing growth and yield.

Lead enters the soil through various anthropogenic and natural pathways. Industrial processes such as mining, smelting, and battery recycling release large quantities of lead into the environment. The extensive use of lead-based fuels in the past has left a legacy of contaminated soils along roadsides and urban areas. Agricultural practices, including the application of lead-containing fertilizers, pesticides, and sewage sludge, further contribute to soil contamination. Natural geochemical processes, such as the weathering of lead-bearing rocks, also play a role, albeit to a lesser extent.

Once in the soil, lead is highly immobile but persists for long periods due to its low biodegradability. It binds strongly to soil particles and organic matter, making it difficult to remove. Despite its immobility, lead can enter the plant system through root absorption and foliar uptake, especially in acidic soils where lead solubility increases. The presence of lead in soil disrupts plant health and productivity, triggering a cascade of adverse effects.

Lead toxicity primarily affects plant physiology by disrupting vital processes, including photosynthesis, respiration, and nutrient uptake.

Lead impairs photosynthesis by affecting chlorophyll synthesis, damaging chloroplast structure, and inhibiting the activity of photosynthetic enzymes. The metal binds to the sulfhydryl groups of enzymes like ribulose-1.5-bisphosphate carboxylase/oxygenase (RuBisCO), reducing their functionality. Additionally, lead-induced oxidative stress generates reactive oxygen species (ROS), which damage thylakoid membranes, further compromising photosynthetic efficiency. Plants exposed to lead often exhibit chlorosis (yellowing of leaves), reduced stomatal conductance, and decreased light absorption.

Lead also interferes with mitochondrial function, inhibiting enzymes involved in the electron transport chain. This disruption impairs ATP production, reducing the energy available for growth and metabolic activities. **Respiratory dysfunction** also exacerbates oxidative stress by increasing the leakage of electrons and ROS generation.

Lead competes with essential nutrients like calcium, magnesium, potassium, and zinc for uptake and transport, causing deficiencies that affect plant health causes **nutrient imbalances**. For example, lead can replace calcium in cell membranes, disrupting membrane stability and permeability. This imbalance not only hampers nutrient availability but also interferes with water transport, leading to wilting and dehydration.

At the biochemical level, lead toxicity induces oxidative stress, enzyme inhibition, and hormonal imbalances that disrupt cellular function.

Crop germination in seeds exposed to Pb toxicity in the soil is the first process in a plant's life to be adversely affected. Toxic accumulation of Pb also interferes with the formation of spindles and the growth of cell walls, decreasing cell expansion and dividing results in inhibition of root volume. During seedling growth and development, roots are more susceptible compared with shoots because they are exposed to Pb toxicity. A well-known index of Pb toxicity tolerance is root growth potential. Under a high Pb toxicity level, plant growth is adversely affected due to poor nutrient uptake and transport. However, lower concentrations of Pb often promote metabolic activities, with enzymes involved in these processes encouraging growth and development.

Lead exposure triggers the **overproduction of ROS**, such as hydrogen peroxide (H_2O_2) and superoxide anions (O_2^-), which damage lipids, proteins, and DNA. Lipid peroxidation of cellular membranes results in leakage of cellular contents and loss of membrane integrity. To counteract **oxidative stress**, plants activate antioxidant defense systems, including enzymes like superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD). However, prolonged exposure to lead overwhelms these defenses, leading to irreversible damage.

Lead binds to functional groups of enzymes, particularly thiol groups, inhibiting their activity. Key enzymes involved in nitrogen metabolism, such as nitrate reductase and glutamine synthetase, are inhibited by lead, reducing nitrogen assimilation and protein synthesis. This impacts growth and metabolic efficiency, further exacerbating the toxic effects of lead.

Lead alters the levels of **phytohormones**, such as auxins, cytokinins, and gibberellins, which regulate plant growth and development. Lead toxicity decreases auxin levels by promoting their oxidation, resulting in stunted growth and abnormal root architecture. The balance between growth-promoting and stress-response hormones is also disrupted, impairing the plant's ability to adapt to environmental challenges.

Lead toxicity manifests in various **morphological abnormalities** in plants, including stunted growth, altered root structure, and reduced reproductive success.

Lead toxicity induces **stunted growth**. Lead inhibits cell division and elongation in meristematic tissues by interfering with DNA synthesis and mitotic spindle formation. This reduces plant height, smaller leaves, and limited biomass production.

The **root system** is the primary site of lead entry into plants and experiences severe **morphological changes** under stress. Lead exposure reduces root elongation, thickens root tips, and increases the formation of lateral roots. These changes result from the accumulation of lead in the root apoplast and the disruption of cellular processes essential for root development. Damaged roots also exude more organic acids and chelators, which increase lead solubility and exacerbate its toxicity.

Lead toxicity affects flowering, fruiting, and seed development by disrupting pollen viability, stigma receptivity, and embryo formation. This leads to **poor reproductive success** and reduced crop yields, significantly threatening agricultural productivity.

Lead toxicity in plants has dire consequences for agriculture and food security. The reduction in crop yields directly affects farmers' livelihoods and the availability of staple foods. Additionally, the accumulation of lead in edible plant parts poses severe health risks to humans and animals. Consuming lead-contaminated crops can cause neurological, renal, and cardiovascular disorders, emphasizing the need for stringent monitoring and regulation.

Lead contamination also perpetuates **soil degradation**. Poor plant growth reduces organic matter inputs to the soil, impairing microbial activity and nutrient cycling. Contaminated plant residues further contribute to the persistence of lead in the soil, creating a vicious cycle of declining fertility and productivity.

Hyperaccumulator plants like *Brassica juncea* and *Helianthus annuus* can absorb and store lead in their tissues, reducing soil contamination. These plants are particularly effective in low to moderate contamination scenarios.

Adding organic matter, biochar, or lime to the soil can immobilize lead, reducing its bioavailability and toxicity. These amendments also improve soil structure and fertility, promoting healthier plant growth.

Developing lead-tolerant crop varieties through genetic engineering offers a promising solution. By enhancing the expression of metal-chelating proteins and antioxidant enzymes, these crops can better withstand lead stress.

Implementing policies to control industrial emissions, reduce lead usage in agriculture, and monitor soil contamination is essential to prevent further pollution.

Educating farmers and communities about the dangers of lead toxicity and promoting sustainable agricultural practices are vital for long-term mitigation.

5.
Principles and Methods of Plant Nutrition

5.1. Principles of Plant Nutrition

Plants are the foundation of life on Earth, providing oxygen, food, fiber, and countless ecosystem services such as regulating climate, maintaining soil health, and supporting biodiversity. To thrive, plants require a balanced supply of nutrients, which they absorb from their surrounding environment. These nutrients are essential for various physiological processes, including growth, reproduction, and resistance to stress. With the global population continuing to rise, ensuring optimal plant nutrition is critical for achieving food security and sustainable agricultural practices.

The study of plant nutrition encompasses the principles governing nutrient absorption, transport, and utilization, as well as the methods used to supply these nutrients effectively. This book explores the core principles of plant nutrition, diverse methods of nutrient delivery, and recent advancements in the field, and discusses challenges and future directions in plant nutrition. Applying these concepts can enhance plant health, increase productivity, and minimize environmental impact.

Liebig's Law of the Minimum, proposed by Justus von Liebig in the mid-19th century, is a principle in agricultural science that emphasizes the importance of nutrient balance in plant growth. According to this law, plant growth is controlled not by the total amount of resources available but by the scarcest resource (limiting factor). Even if all other nutrients are abundant, a deficiency in just one essential element will limit plant growth.

Liebig illustrated this concept with his famous "barrel analogy", where a wooden barrel represents different nutrients as staves of varying lengths. The shortest stave determines how much water the barrel can hold, symbolizing that the nutrient in the lowest supply restricts the plant's potential growth.

Mitscherlich's Law of Diminishing Returns, introduced by Eilhard Alfred Mitscherlich, expands on Liebig's principle by explaining the relationship between nutrient application and plant growth. This law states that the increase in crop yield resulting from the application of a nutrient is not directly proportional to the amount applied. Instead, the first increments of the deficient nutrient have the most significant impact on growth. As more of the nutrient is added, the yield gain gradually decreases until no further increase occurs, even with additional inputs. Mitscherlich's law highlights the importance of optimizing fertilizer use. Over-application may not only be inefficient but can also lead to environmental concerns such as nutrient runoff.

While Liebig's Law emphasizes the limiting factor – the nutrient in the shortest supply restricts growth, Mitscherlich's Law describes the diminishing returns of nutrient application, showing that excessive supplementation yields progressively smaller benefits.

Together, these principles form the foundation of modern nutrient management strategies, guiding farmers and agronomists to achieve efficient and sustainable crop production.

Plants require 17 **essential nutrients** to complete their life cycle. These nutrients are considered essential because they fulfill the following criteria; they are necessary for normal growth and reproduction, they cannot be replaced by different elements, and they have one or more roles in plant metabolism. Essential nutrients are classified into macronutrients and micronutrients based on their relative quantities in plant tissues. **Macronutrients** are required in larger quantities and include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S) carbon (C), hydrogen (H), and oxygen (O). These nutrients play a critical role in plant nutrition. For example, nitrogen is vital for chlorophyll synthesis, while phosphorus is essential for energy transfer and root development. **Micronutrients** are needed in smaller amounts but are equally important. These eight essential micronutrients include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), chlorine (Cl), nickel (Ni), and molybdenum (Mo). Micronutrients often serve as co-factors in enzymatic reactions.

A deficiency or toxicity of any nutrient can lead to physiological disorders and reduced plant productivity. Understanding the specific roles and symptoms associated with each nutrient helps in diagnosing and addressing deficiencies effectively.

Plants absorb nutrients primarily through their roots, which interact with the soil to extract water and nutrients. Nutrient uptake occurs via two primary mechanisms:

i. The movement of nutrients into a plant without the use of cellular energy is known as **passive nutrient transport**. This mostly happens through the natural flow of water and concentration gradients; the most prevalent examples are mass flow and diffusion, where nutrients are transported through the roots along with water uptake.
ii. A process known as **active transport** uses stored energy to deliver nutrients against an electrochemical/concentration gradient. For example, proton pumps in root cells facilitate the uptake of potassium and nitrate ions.

Root architecture plays a critical role in nutrient uptake. Deep-rooted plants can access nutrients from deeper soil layers, while fibrous roots are more effective in exploring surface soils. The rhizosphere, the region of soil surrounding plant roots, is a hotspot for nutrient exchange. Plants release exudates, such as organic acids and enzymes, which alter soil pH and enhance nutrient availability. For instance, organic acids can solubilize phosphorus bound to soil particles, making it accessible to plants.

Soil type significantly influences nutrient availability. Sandy soils, for example, have low nutrient retention, while clay soils can bind nutrients tightly, reducing their availability.

Nutrient cycling is a natural process that replenishes essential elements in the soil. The **nitrogen cycle** involves the breakdown of the double bond of the gaseous nitrogen by lightning, nitrogen fixation by bacteria, ammonification, nitrification, and denitrification. These processes convert atmospheric nitrogen into plant-available forms and return excess nitrogen to the atmosphere.

Unlike nitrogen, phosphorus (P) lacks a gaseous phase and is primarily replenished through rock weathering and organic decomposition. It cycles between soil, plants, and organic matter. In natural systems, phosphorus is derived from the weathering of phosphate-rich rocks and minerals, while fertilizers supply it by processing these phosphate sources to release P into the soil and water. Phosphorus is available for plant uptake in the form of phosphate ions in the soil and dissolved orthophosphate in water bodies. On land, phosphorus is found in soil, particulate matter, and dissolved organic matter. In water, it moves between sediments and the water column. Phosphate ions (PO_4^{3-}), are taken up by plants through the root system from the soil. Phosphorus is essential for plant nutrition as it is a key component of DNA, RNA, ATP, and cellular membranes.

Understanding nutrient cycles helps in designing sustainable fertilization practices that align with natural processes.

5.2. Methods of Plant Nutrition

5.2.1. Fertilizers

Fertilizers are critical components of modern agriculture, providing essential nutrients that enhance soil fertility and promote healthy plant growth. The efficient and appropriate application of fertilizers is vital for achieving maximum agricultural productivity while minimizing environmental impacts. Several methods are used to apply fertilizers, each tailored to specific crops, soil conditions, and farming practices.

Although fertilizers can be supplied foliar, soil-based fertilization is the most traditional and widely used method of supplying nutrients to plants.

Organic fertilizers are derived from natural sources like compost, manure, and bone meal. Organic fertilizers improve soil health by enhancing microbial activity and increasing organic matter content.

Synthesized **inorganic fertilizers** such as urea, diammonium phosphate (DAP), and muriate of potash (MOP) provide nutrients in readily available forms, offering quick results. However, they require careful management to prevent leaching and environmental harm. Here are several methods for applying fertilizers, with **broadcasting** being one of the most common. This method involves uniformly distributing fertilizers across the field. It is widely employed for crops that cover large areas, such as wheat, rice, and other cereals. Application using this method involves spreading fertilizer before or during sowing to prepare the soil for planting (basal application). During the crop's growth period, a secondary application, known as top dressing, is applied to replenish the used-up nutrients.

Advantages:

- It covers extensive areas quickly and uniformly.
- It requires minimal technical expertise, making it accessible for small-scale farmers with limited agricultural machinery.
- It is suitable for crops with dense planting patterns.

Disadvantages:

- High nutrient loss probability through runoff, volatilization, and leaching.
- May result in uneven nutrient distribution, causing over-fertilization in some areas and deficiencies in others.
- Fertilizers may be inefficiently used as they are dispersed across non-crop areas.

To reduce nutrient losses, broadcasting is most effective when combined with proper irrigation and soil management practices.

Effective **fertilizer application** is crucial for maximizing crop yield and minimizing nutrient loss. Different methods offer distinct benefits depending on soil conditions, crop types, and environmental factors.

Fertilizer methods can be broadly categorized into surface broadcast, plowdown, band application, and row application.

Surface application when fertilizer is applied directly to the soil surface without incorporation. This method is commonly used for pastures, lawns, and cereal crops.

Advantages:

- Simple and quick application.
- Requires minimal equipment.
- Effective for top-dressing crops during active growth.

Disadvantages:

- Nutrients, especially nitrogen, are prone to volatilization and runoff if not followed by rainfall or irrigation.
- Risk of uneven nutrient distribution.
- Limited root zone penetration, especially in dry conditions.

Broadcast incorporated/plowdown application when fertilizer is evenly spread across the soil surface and then mixed into the soil using tillage equipment.

Advantages:

- Provides uniform nutrient distribution across the field.
- Reduces nutrient loss from volatilization by incorporating the fertilizer into the soil.
- Suitable for pre-plant fertilization and bulk nutrient application.

Disadvantages:

- Requires additional labor and equipment for incorporation.
- Potentially inefficient if plant roots are concentrated in specific zones.
- May disturb soil structure and increase erosion risk in certain conditions.

Band application is when fertilizer is placed in concentrated bands either on the soil surface or below the soil near the seed row.

Advantages:

- Provides nutrients close to plant roots, improving early growth and nutrient uptake.
- Reduces fertilizer contact with soil, minimizing nutrient fixation and improving phosphorus availability.
- Efficient for crops with high nutrient demands during early growth stages.

Disadvantages:

- May require specialized equipment.
- Risk of root injury if fertilizer concentration is too high.
- Limited coverage may leave some areas under-fertilized.

Row application when fertilizer is applied directly along the crop rows during planting or early growth stages. It is often combined with seeding operations.

Advantages:

- Ensures nutrients are available in the root zone.
- Efficient for row crops like maize, wheat, and soybeans.
- Reduces overall fertilizer use by targeting plant roots directly.

Disadvantages:

- Requires precise application equipment.
- Can increase the risk of root damage if applied too close to seeds.
- May require multiple applications for crops with spreading root systems.

Foliar feeding fertilizer application involves spraying nutrient solutions directly onto plant leaves. This method is particularly effective for micronutrients like zinc and iron, as they can be absorbed quickly through the leaf surface. Foliar feeding is often used to address deficiencies during critical growth stages. Advantages of foliar feeding include rapid correction of deficiencies and minimal nutrient loss. However, it is not a substitute for soil fertilization, as only small amounts of nutrients can be delivered via this method.

The drip fertigation method integrates fertilizers into drip irrigation systems, delivering nutrients along with water directly to the root zones of plants. This precision method is becoming increasingly popular in modern agriculture.

Advantages:

- Enhances water and nutrient use efficiency by targeting the root zone.
- Reduces nutrient losses due to leaching and runoff.
- Promotes uniform crop growth and higher yields.
- Saves labor by combining irrigation and fertilization in a single process.

Disadvantages:

- The high initial cost of setting up drip irrigation systems.
- Requires technical expertise to manage fertilizer concentrations and application timing.
- Limited to crops that benefit from drip irrigation, such as vegetables, fruits, and high-value crops.
- Drip fertigation is especially beneficial in water-scarce regions where resource efficiency is paramount.

Side-dressing is a method of applying fertilizers to growing crops by placing them in the soil near the plant rows or between the rows. Unlike basal applications, which are done before or during planting, side-dressing is performed during the growing season, when plants have already established roots. This method ensures that nutrients are available at specific growth stages when the plants need them the most, such as during vegetative growth or fruit development.

Side-dressing can be performed using different techniques depending on the crop type, field conditions, and the equipment available. In small-scale farming, fertilizers are applied **manually**, usually with a hand-held tool or by sprinkling granular fertilizers alongside the plant rows. While labor-intensive, this method allows precise placement in areas where machinery cannot be used. In larger fields, side-dressing is done using **specialized machinery** such as side-dress applicators or cultivators fitted with fertilizer dispensers. These machines ensure uniform application and reduce labor requirements.

Shallow **furrows** are created alongside the plant rows, and fertilizers (granular/ powdered) are placed within them. The furrows are then covered with soil to protect the nutrients and minimize losses.

Alternatively, liquid fertilizers such as urea ammonium nitrate (UAN) solutions, are **injected** into the soil near the root zone using injection systems. This method ensures efficient nutrient uptake and reduces environmental losses.

Side-dressing is particularly beneficial for crops that have high nutrient demands during specific growth stages.

Nitrogen side-dressing is critical for maximizing yields, especially during the rapid growth phase after the V6 (six-leaf) stage of maize. Crops like tomatoes, peppers, and cucumbers benefit from side-dressing during flowering and fruit development to enhance quality and yield. Wheat and barley often require additional nitrogen during the tillering or jointing stages. Potatoes, carrots, and onions benefit from side-dressing with nitrogen and potassium to ensure proper tuber and bulb formation. Side-dressing provides nutrients during the vegetative and early reproductive stages, ensuring robust growth and boll development.

Side-dressing offers several **benefits** that make it a preferred method for applying fertilizers during crop growth.

Advantages:

- By placing fertilizers near the plant roots, side-dressing ensures that nutrients are readily available for uptake. This targeted delivery reduces wastage and enhances nutrient use efficiency.
- Farmers can adjust side-dressing schedules based on crop growth stages and nutrient requirements, allowing for timely interventions.
- Covering the applied fertilizers with soil minimizes losses due to volatilization, leaching, and runoff, making this method environmentally friendly (reduces the risk of nutrients leaching into groundwater or runoff into surface water, which are major contributors to water pollution and eutrophication).
- Provides plants with additional nutrients during critical growth phases, promoting vigorous development and higher yields.
- By applying fertilizers only when and where needed, side-dressing reduces the total amount of fertilizer required, lowering input costs (lowering the carbon footprint associated with fertilizer production and transportation.

Despite its advantages, side-dressing has certain **limitations** that need to be addressed for effective implementation:

- Manual side-dressing is labor-intensive and time-consuming, making it less suitable for large-scale farming.
- Mechanical side-dressing requires specialized equipment, which may be expensive for small-scale farmers.
- Delayed or poorly timed side-dressing can result in suboptimal nutrient uptake, affecting crop performance.
- The process of side-dressing may disturb the soil and roots, especially if done carelessly or with inappropriate tools.
- In dry climates or during periods of drought, side-dressed fertilizers may not dissolve effectively, reducing their availability to plants. If not managed properly, side-dressing can lead to over-application of fertilizers, causing nutrient imbalances and environmental harm.

Side-dressing can play a significant role in promoting environmentally sustainable agriculture. Therefore, farmers must adopt precision techniques and adhere to recommended guidelines to ensure that side-dressing benefits both agriculture and the environment.

Liquid fertilizer **injection** is a method of applying fertilizers in liquid form directly into the soil using specialized equipment. This technique ensures that nutrients are delivered to the root zone, where they can be readily absorbed by plants. The process often involves injecting the liquid fertilizers at varying depths depending on the crop type, soil conditions, and specific nutrient requirements. This method is particularly beneficial for applying macronutrients like nitrogen, phosphorus, and potassium and is frequently used in large-scale farming operations and high-value crop production. Liquid fertilizer injection can be performed using different methods, each suited to specific agricultural scenarios.

Anhydrous ammonia injection method involves injecting anhydrous ammonia (a nitrogen-rich fertilizer) into the soil at a depth where it reacts with moisture to form ammonium, a plant-available form of nitrogen. It is commonly used in cereal and grain production.

Knifing involves using specialized equipment fitted with narrow blades or "knives" to open the soil, where liquid fertilizers are injected and immediately covered. This method minimizes nutrient losses and is ideal for row crops like corn and soybeans.

Drip injection integrates liquid fertilizers into drip irrigation systems, delivering nutrients and water simultaneously to the root zone. It is widely used in horticulture and high-value crop production.

In livestock farming, nutrient-rich manure **slurry** is **injected** into the soil as a liquid fertilizer. This method not only recycles waste but also enriches the soil with organic matter.

The subsurface injection method involves placing fertilizers below the soil surface, often at depths of 6 to 12 inches. It is used to prevent nutrient losses through volatilization and runoff.

Deep placement of fertilizers refers to the application of nutrients at a specific depth in the soil, near the root zone of plants. Unlike surface application methods, deep placement positions the fertilizer in a concentrated form, often as compacted briquettes, granules, or liquid injections. This localized delivery ensures that nutrients are readily accessible to plant roots, promoting optimal growth and reducing wastage. This method is particularly effective for nitrogen and phosphorus fertilizers, which are prone to losses through volatilization, runoff, and leaching when applied on the surface. Deep placement is commonly used for crops like rice, maize, sugarcane, and other cereals and vegetables.

Top-dressing is the surface application of fertilizers during the growth phase of crops, typically when plants are actively developing and require additional nutrients. Unlike basal application, which is performed before or during planting, top-dressing is applied after crop emergence to address nutrient deficiencies or support key developmental stages. It is commonly used for nitrogen-rich fertilizers such as urea, ammonium nitrate, and potassium nitrate. This method is particularly effective for cereals, vegetables, and other nutrient-intensive crops that demand sustained nutrient availability throughout their growth cycle.

Starter fertilization refers to the application of small amounts of nutrients placed near the seed at planting to promote early seedling growth. This method provides young plants with easily accessible nutrients during their critical early development stages, improving root establishment and overall crop vigor.

Micro starter fertilizers are specialized formulations designed for precise nutrient delivery, often applied in concentrated zones close to the seed. Before micro starter fertilization some facts should be considered. Starter fertilizers are particularly beneficial in cold, wet, or compacted soils where nutrient uptake is limited. Row crops like maize, wheat, and soybeans often respond well to starter fertilization. Accurate rate control is crucial to prevent seed injury, especially when using pop-up or seed placement methods. Common methods for applying starter and micro starter fertilizers include pop-up, in-furrow, and seed placement techniques.

Pop-up fertilizers are placed directly in the seed furrow at planting, ensuring immediate nutrient availability.

Advantages:
- Provides rapid access to nutrients, enhancing early root and shoot growth.
- Ideal for cool, wet soils where nutrient availability may be limited.
- Efficient for crops with a short growing season.

Disadvantages:
- Risk of seed injury due to salt damage or ammonia toxicity if applied at excessive rates.
- Requires precise rate control to avoid harming seedlings.

Furrow fertilizers are applied directly in the planting furrow, often just below or beside the seed. This method is similar to pop-up fertilization but may involve slightly greater separation from the seed.

Advantages:
- Provides nutrients in the root zone, improving early root establishment.
- Efficient for crops that require a strong early growth phase.
- Reduces nutrient loss by placing fertilizer directly in moist soil.

Disadvantages:
- Potential for seed injury if fertilizer rates are too high.
- Specialized equipment may be required for precise placement.

Seed placement fertilizer is placed in direct contact with the seed during planting. This method is designed to deliver nutrients immediately at germination.

Advantages:

- Maximizes early nutrient uptake.
- Effective for micronutrient delivery, particularly phosphorus, zinc, and boron.
- Promotes uniform seedling emergence.

Disadvantages:

- Higher risk of seed damage due to salt concentration or nutrient toxicity.
- Careful calibration of equipment and fertilizer rates is essential.

Starter fertilization techniques, including pop-up, in-furrow, and seed placement methods, play a vital role in promoting early crop growth. While these methods can significantly improve yield potential, careful management is essential to balance nutrient supply with the risk of seed injury. Selecting the right method and fertilizer formulation based on soil conditions and crop needs ensures optimal results.

5.2.2. Alternative Methods of Fertigation

Alternative plant nutrition refers to methods and practices that provide essential nutrients to plants through means other than conventional chemical fertilizers. These approaches focus on utilizing natural, organic, or bio-based sources of nutrients, often enhancing soil fertility and biological activity in the process.

The core objectives of alternative plant nutrition include:

- Reducing reliance on synthetic fertilizers.
- Improving nutrient use efficiency.
- Enhancing soil health and sustainability.
- Minimizing environmental impacts.
- Supporting long-term agricultural productivity.

Various techniques and strategies have been developed to provide plants with nutrients through alternative means. These include organic amendments, biological solutions, and innovative technologies.

Organic fertilizers are derived from natural sources such as plant residues, animal waste, and mineral deposits. They provide nutrients in a slow-release form, improving soil structure and microbial activity.

Biological approaches harness the power of soil microorganisms to enhance nutrient availability and uptake by plants. Natural substances or microorganisms that enhance plant growth and nutrient uptake by stimulating biological processes. **Biofertilizers** contain living microorganisms, such as nitrogen-fixing bacteria (e.g., *Rhizobium*) and phosphate-solubilizing bacteria that improve nutrient availability. **Mycorrhizal fungi** form associations with plant roots, increasing nutrient and water absorption.

Alternative plant nutrition represents a paradigm shift in agricultural practices, focusing on sustainable, eco-friendly, and resource-efficient methods of providing nutrients to crops. By adopting approaches such as organic fertilizers, biofertilizers, integrated nutrient management, and soil-less cultivation, farmers can reduce dependency on synthetic fertilizers and address environmental challenges.

While challenges remain, advances in technology, education, and policy support are paving the way for the widespread adoption of alternative plant nutrition. As global agriculture faces the dual challenge of increasing food production and preserving natural resources, these innovative methods will play a crucial role in shaping a sustainable and resilient farming future.

6.
Alternative Plant Nutrition

As the global population continues to rise, the demand for agricultural production intensifies. However, conventional farming practices, particularly the reliance on synthetic fertilizers, pose significant environmental challenges such as soil degradation, water pollution, and greenhouse gas emissions. The quest for sustainable agricultural systems has spurred interest in alternative plant nutrition strategies that can maintain crop productivity while reducing environmental impact. These alternatives focus on leveraging organic, biological, and industrial resources to create efficient and eco-friendly nutrient management systems.

In agriculture, plant nutrition plays a fundamental role in ensuring healthy growth, optimal yields, and soil fertility. While synthetic fertilizers have been the dominant source of plant nutrients for decades, their extensive use has led to several environmental and economic challenges. Issues such as soil degradation, water pollution, greenhouse gas emissions, and high costs have prompted the search for sustainable alternatives. Alternative plant nutrition materials offer viable solutions, providing nutrients through eco-friendly and resource-efficient means.

6.1. Exploring the Need for Alternative Plant Nutrition Materials

Overuse of synthetic fertilizers leads to nutrient runoff, causing eutrophication in water bodies and biodiversity loss.

Synthetic fertilizers have played a crucial role in transforming agriculture, significantly enhancing crop yields and meeting the nutritional demands of a growing global population. However, their overuse has led to unintended and far-reaching environmental consequences. Among these, nutrient runoff into water bodies and the resulting eutrophication stand out as major issues, causing biodiversity loss and ecosystem degradation.

Table 2 shows the limit values and samples values of biologically treated slaughterhouse technological wastewater, biowaste compost, and compost. The utilization of these by-products in agriculture offers valuable opportunities to recycle nutrients, improve soil quality, and reduce waste. However, their application requires careful management to ensure environmental protection, crop safety, and compliance with legal standards. Slaughterhouse wastewater is rich in organic matter, nitrogen, phosphorus, and other nutrients essential for plant growth. However, untreated wastewater poses serious environmental risks due to its high biological oxygen demand and potential pathogen content. Biological treatment methods, such as activated sludge systems, constructed wetlands, or anaerobic digestion, are employed to reduce contaminants and stabilize the wastewater for safe agricultural use. Biowaste compost is produced from organic kitchen waste, garden residues, and other biodegradable materials. Through controlled aerobic decomposition, the resulting compost is rich in organic matter, humus, and nutrients that enhance soil fertility.

Table 2: The limit values and samples values of biologically treated slaughterhouse technological wastewater (1), biowaste compost (2), and compost (3).

Parameters	(1)		(2)		(3)	
	Limit	Sample	Limit	Sample	Limit	Sample
	mg/l		mg/kg DM		kg/ha/year	mg/kg DM
Al	10	nd	–	–	–	–
As	0.2	0.0069	25	<5	0.5	3.43
B	0.7	nd	–	–	–	–
Ba	4	nd	–	–	–	–
Cd	0.02	nd	5	0.33	0.15	0.2075
Co	0.05	nd	50	0.8	0.5	0.79
ΣCr	2.5	nd	350	9.34	10	4.13
Cu	2	<0.05	750	53.9	10	16.1
Hg	0.01	<0.002	5	0.51	0.1	0.05
Mn	5	0.04	–	–	–	–
Mo	0.02	nd	10	4	0.2	1
Ni	1	nd	100	10.5	2	4.515
Pb	1	nd	400	<2.0	10	2.5
Se	no limit	0.29	50	<1.25	1	4
Zn	5	0.04	2000	360	30	83.65
Cl^-	150	94	–	–	–	–
Animal and vegetable fats	200	<2	–	–	–	–
Anionic surfactant	30	<0.1	–	–	–	–

nd = not detected, DM = dry matter

Source: Own data

Synthetic fertilizers are chemical compounds primarily composed of nitrogen, phosphorus, and potassium (NPK), essential macronutrients for plant growth. They provide readily available nutrients, ensuring rapid uptake and improved yields. However, when applied excessively or inefficiently, a significant portion of these nutrients escapes into the environment instead of being absorbed by plants because plants can only take up nutrients at a certain rate, and any excess remains unused in the soil. Rainfall or irrigation practices then carry these surplus nutrients away from the soil, leading to runoff into nearby water bodies, and contributing to environmental problems such as eutrophication. In this process, excess nutrients in water stimulate the overgrowth of algae, which depletes oxygen levels and harm aquatic ecosystems.

The use of alternative plant nutrition materials such as organic fertilizers or bio-based products, offers numerous **advantages** over conventional synthetic fertilizers.

- Reduction of nutrient runoff and pollution, protecting water bodies and ecosystems.
- Minimized greenhouse gas emissions associated with fertilizer production and application. Alternative materials typically have a lower carbon footprint, contributing to climate change mitigation.
- Improved soil structure, microbial activity, and water retention.
- Reduced soil degradation and fosters long-term fertility.
- Utilization of locally available resources, such as compost and manure, reduces input costs.
- A sustainable solution for resource-poor farmers.
- Promotion of recycling and reuse of waste materials, reducing the burden on landfills.
- Improved plants' ability to withstand environmental stresses, such as drought.

Despite their benefits, alternative plant nutrition materials face **challenges** that limit their widespread adoption:

- Organic and mineral-based materials release nutrients slowly, which may not meet the immediate needs of high-yielding crops.
- Producing, processing, and applying these materials require labor and infrastructure, which may not be readily available.
- Farmers may lack the awareness or technical expertise to utilize these materials effectively.
- Producing sufficient quantities of alternative materials for large-scale farming is a significant challenge.
- The use of waste-derived materials may face regulatory restrictions due to potential contamination risks.

Alternative plant nutrition strategies offer transformative potential for creating a more sustainable and resilient agricultural system. By leveraging organic materials, biological processes, industrial by-products, and innovative technologies, these solutions address the limitations of conventional fertilizers while promoting environmental health and economic viability. Despite challenges such as nutrient variability and scalability, continued research, education, and policy support can drive the adoption of these alternatives. Embracing sustainable plant nutrition is not merely an environmental necessity; it is a critical step toward ensuring global food security and agricultural sustainability for future generations.

7.
Concept and Grouping of Industrial Waste and By-Products

Industrialization has been a driving force in shaping modern economies and societies, enabling large-scale production, innovation, and economic growth. However, the industrial processes that generate essential goods and services also produce significant amounts of waste and by-products. These materials, if not managed effectively, can pose environmental, economic, and social challenges. Understanding the concept and classification of industrial waste and by-products is crucial for addressing these challenges and fostering sustainable industrial practices.

Industrial waste and by-products are materials generated during industrial and manufacturing processes. While they may seem similar, the terms have distinct meanings and implications for resource management.

Industrial waste refers to residual materials that are considered unusable or undesired at the end of an industrial process. These materials are often discarded and require proper treatment or disposal to prevent environmental harm. Examples include slag from metal smelting, chemical residues, and construction debris.

By-products are secondary materials produced alongside the primary product during an industrial process. Unlike waste, by-products often have intrinsic value and can be reused, sold, or transformed into useful products. Examples include sawdust from timber processing, glycerol from biodiesel production, and molasses from sugar manufacturing.

The distinction between waste and by-products depends on the material's potential for reuse or recycling. Effective resource management seeks to minimize waste generation and maximize the utility of by-products, aligning with the principles of a circular economy.

Industrial waste and by-products can be **classified** based on their physical state, source, chemical composition, and potential for reuse. Grouping these materials helps in developing targeted strategies for management, reuse, and disposal.

7.1. Classification by Physical State

- Solid Waste: Includes non-liquid materials such as scrap metal, packaging waste, plastics, and construction debris.
  Examples: Steel scraps, sawdust, and concrete rubble.
- Liquid Waste: Consists of liquid residues and effluents generated during industrial processes.
  Examples: Wastewater from textile dyeing, oil spills, and chemical solutions.
- Gaseous Waste: Includes emissions released during combustion, chemical reactions, or manufacturing.
  Examples: Carbon dioxide, sulfur dioxide, and volatile organic compounds (VOCs).
- Sludge: Semi-solid residues generated from wastewater treatment or industrial processes.
  Examples: Sludge from paper mills and oil refineries.

7.2. Classification by Source

- Manufacturing Waste: Generated during the production of goods in industries like textiles, chemicals, and automotive manufacturing.
  Examples: Paint residues, fabric trimmings, and off-spec products.
- Mining and Quarrying Waste: Produced during the extraction of minerals and resources.
  Examples: Overburden, tailings, and slag.
- Construction and Demolition Waste: Arises from construction, renovation, and demolition activities.
  Examples: Concrete, bricks, and wood.
- Energy Production Waste: Generated during power generation processes, especially in thermal power plants.
  Examples: Fly ash, bottom ash, and flue gas desulfurization sludge.

7.3. Classification by Hazardous Nature

Figure 4 shows the classification of waste material by its hazardous or non-hazardous nature. All waste that has not been categorized as hazardous, such as food waste, paper, packaging materials, plastics, glass, metal, beverage cans, and organic waste, is referred to as **non-hazardous** or solid waste. Solid waste is not dangerous, but if it is not collected and processed, it can have detrimental effects on the environment and human health. Theoretically, a sizable amount of solid waste may be recycled or reused, but one of the most waste management issues is the need for selective garbage collection, which is a requirement for recycling and reuse.

Waste classified as **hazardous** requires special, distinct handling and treatment since it has been determined that it may endanger human health and the environment. The precise collection and recycling procedure is determined by physical and chemical properties. Hazardous waste is characterized by its flammability, corrosiveness, toxicity, ecotoxicity, and explosiveness. To prevent contact with non-hazardous trash, separate collection and processing procedures are typically created. Hazardous waste can be treated via chemical treatment, incineration or high-temperature treatment, safe storage, recovery, and recycling. Waste that is liquid, gaseous, or granular requires particular treatment by default to prevent waste from spreading. Examples of hazardous waste include asbestos, chemical solvents, and heavy metals. The majority of hazardous waste comes from manufacturing.

7.4. Classification by Potential for Reuse

Waste can be classified according to its ability to be reused, decomposed, or converted into energy, with each category contributing uniquely to waste management and sustainable practices.

- Recyclable Waste: Materials that can be processed and reused in new products.
  Examples: Scrap metals, plastics, and paper.
- Non-Recyclable Waste: Waste that cannot be economically recycled and often requires disposal.
  Examples: Contaminated materials and mixed waste.
- Compostable Waste: Organic materials that can decompose into nutrient-rich compost.
  Examples: Food scraps and agricultural residues.
- Energy-Recoverable Waste: Waste materials that can be converted into energy through incineration or bio-digestion.
  Examples: Used tires and biomass.

Industrial waste and by-products are inevitable by-products of economic progress, but they do not have to be a liability. By understanding their nature and classification, industries can adopt effective management strategies that reduce environmental harm and enhance economic efficiency. Recycling, reuse, and technological innovations are key to transforming waste into resources, supporting a circular economy that prioritizes sustainability.

As global industries face growing pressures to balance production with environmental stewardship, a comprehensive approach to managing industrial waste and by-products will be crucial. By integrating policy, technology, and innovation, societies can ensure a cleaner, greener future that aligns industrial growth with ecological responsibility.

8. Management, Placement, Prohibition of the Use of Industrial Wastes, and Legal Regulation

The rapid growth of industrialization has significantly contributed to economic development and technological advancement. However, this progress comes at an environmental cost, particularly through industrial waste generation. Proper management, placement, and prohibition of inappropriate waste practices are critical to mitigate the adverse effects of industrial waste on ecosystems, public health, and climate. Legal regulations are pivotal in ensuring compliance and sustainable waste management practices. This chapter explores the importance of industrial waste management, the principles of waste placement, the prohibition of harmful practices, and the legal frameworks governing industrial waste.

8.1. Industrial Waste Management

Industrial waste refers to by-products from industrial processes, including chemicals, metals, plastics, sludges, and gases. Managing these wastes is vital to protect the environment and human health while promoting resource recovery and sustainable practices. Effective industrial waste management involves several key principles:

The **waste hierarchy** emphasizes reducing, reusing, and recycling waste before considering disposal. It encourages industries to minimize waste generation at the source, repurpose materials, and recycle valuable components. For instance, scrap metals from manufacturing can be recycled, reducing the demand for virgin materials.

Proper **classification of industrial waste** is essential for determining its management strategy. Waste can be categorized as hazardous or non-hazardous (see section 4.3 for details).

Industries employ various treatment technologies to manage waste.

- Thermal Treatment: Incineration or pyrolysis to reduce waste volume and generate energy.
- Chemical Treatment: Neutralization of hazardous chemicals to render them non-toxic.
- Biological Treatment: Using microbes to break down organic waste, such as in anaerobic digestion.

- A circular economy approach integrates waste management into production cycles, ensuring that industrial by-products are reused or recycled. This approach not only reduces waste but also conserves resources and minimizes environmental impact.

8.2. Placement of Industrial Wastes

Proper placement of industrial waste is crucial to avoid environmental degradation and ensure public safety. Placement refers to the controlled storage, disposal, or recycling of waste in designated areas that adhere to safety and environmental standards.

Landfills are a common method for the disposal of industrial waste. Modern sanitary landfills are designed with protective liners, leachate collection systems, and methane capture technologies to prevent soil and water contamination. Hazardous waste landfills are subject to even stricter controls to ensure containment.

Recycling facilities process industrial wastes like metals, plastics, and paper into reusable materials. Proper placement of recyclable waste in designated facilities maximizes resource recovery and reduces the burden on landfills.

Certain types of industrial waste require **temporary storage** before final treatment or disposal. These storage facilities must meet safety standards to prevent leaks, spills, or accidental exposure.

Waste-to-energy plants convert non-recyclable waste into usable energy, such as electricity or heat. These facilities must be strategically located to minimize transport costs and environmental impact.

8.3. Prohibition of Inappropriate Industrial Waste Practices

The improper handling and disposal of industrial waste can have severe consequences, including soil and water contamination, air pollution, and harm to human and ecological health. To mitigate these risks, several practices are strictly prohibited:

- Dumping industrial waste in unauthorized locations, such as rivers, forests, or open fields, is a major environmental crime. This practice leads to pollution, ecosystem degradation, and public health risks.
- Open burning of hazardous waste releases toxic pollutants, such as dioxins and furans, into the atmosphere. Such practices are prohibited to prevent air pollution and respiratory diseases.
- Mixing hazardous and non-hazardous waste complicates treatment and recycling processes and increases the risk of contamination. Regulations prohibit this practice to ensure safe and efficient waste management.
- The illegal export of industrial waste to countries with weak environmental protection regulations is a growing concern. This practice violates international agreements and often results in improper disposal in the receiving country.

8.4. Legal Regulation of Industrial Waste

Effective legal frameworks are essential for enforcing responsible industrial waste management practices and preventing environmental harm. Regulations typically address waste generation, handling, treatment, and disposal. Legal regulations include penalties for non-compliance, such as fines, license revocation, or imprisonment. Regulatory bodies conduct inspections, audits, and monitoring to enforce compliance and ensure adherence to waste management standards.

8.4.1. International Regulations

Global cooperation is essential for addressing agricultural waste management, especially in regions where cross-border trade and environmental impacts are significant. Several international agreements and conventions provide guidelines for agricultural waste management:

- **Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal**
  Although primarily focused on hazardous waste, the Basel Convention also covers agricultural waste containing toxic substances like pesticides and fertilizers. It regulates the export, import, and disposal of hazardous agricultural wastes to ensure they are managed in an environmentally sound manner.
- **Stockholm Convention on Persistent Organic Pollutants (POPs)**
  This convention targets harmful chemicals, including pesticides like DDT, often found in agricultural waste. By regulating and restricting POPs, the Stockholm Convention minimizes their release into the environment, promoting safer agricultural waste management practices.
- **Minamata Convention on Mercury**
  The Minamata Convention addresses mercury pollution, which can arise from the use of mercury-based pesticides in agriculture. It emphasizes the need for safer alternatives and proper disposal of mercury-containing wastes.
- **Sustainable Development Goals (SDGs)**
  The United Nations SDG 12 emphasizes responsible consumption and production, urging countries to adopt sustainable waste management practices, including agricultural waste recycling and reuse.

8.4.2. National Regulations

National governments enact laws and policies tailored to their unique agricultural and environmental contexts. Effective national legal frameworks encompass waste management, pollution control, and resource recovery.

India has developed comprehensive laws to address agricultural waste. Solid Waste Management Rules encourage composting and recycling organic agricultural waste.

Bio-Medical Waste Management Rules are primarily for medical waste, they apply to agricultural settings like poultry farms and veterinary practices that generate biohazardous waste.

In the **United States**, the Resource Conservation and Recovery Act (RCRA) governs the disposal of agricultural waste, particularly hazardous materials like pesticides and fertilizers. It emphasizes waste minimization, recycling, and safe disposal.

The **EU**'s Waste Framework Directive sets the legal framework for waste management across member states. It prioritizes the waste hierarchy – prevention, reuse, recycling, recovery, and disposal – encouraging sustainable practices in agricultural waste management.

China's law promotes the reuse and recycling of agricultural by-products, such as crop residues and animal manure. It incentivizes the development of technologies for waste-to-energy and composting.

Local governments often develop specific regulations to address unique agricultural waste challenges in their regions. These regulations ensure compliance with national laws while accommodating local practices.

Local authorities regulate the placement of waste treatment facilities, such as composting units or biogas plants, to minimize environmental and social impacts.

Regions with intensive livestock farming require manure management plans to prevent nutrient runoff into water bodies. These plans outline storage, treatment, and application protocols for animal waste.

Farmers may need permits to store, transport, or dispose of agricultural waste (farm waste permits). These permits ensure adherence to legal standards and reduce the risk of improper waste management.

8.4.3. Regulations in Hungary

Hungary, as a member of the European Union (EU), is committed to sustainable waste management practices, including the utilization of industrial wastes and by-products. The country's legal frameworks are aligned with EU directives while incorporating specific national policies to address local industrial and environmental challenges. These laws aim to promote the circular economy, reduce environmental pollution, and support the efficient use of resources. This section explores the legal frameworks governing the use of industrial wastes and by-products in Hungary, including their alignment with EU legislation, national laws, and challenges in implementation.

Overview of Industrial Waste Management in Hungary

Hungary generates significant amounts of industrial waste from sectors such as manufacturing, mining, construction, and energy production. Effective utilization of these wastes and by-products is critical for minimizing environmental impacts and advancing sustainability goals. The legal framework for managing industrial waste in Hungary is designed to ensure environmentally sound practices while promoting waste as a resource through recycling and recovery.

As an EU member state, Hungary is obligated to comply with EU waste management directives. These directives provide the foundation for Hungary's industrial waste policies:

- **Waste Framework Directive (2008/98/EC)**
  The Waste Framework Directive establishes the EU's waste hierarchy, prioritizing waste prevention, reuse, recycling, recovery, and disposal. Hungary has transposed this directive into national law, emphasizing resource efficiency and the circular economy.
- **Landfill Directive (1999/31/EC)**
  This directive limits the disposal of waste in landfills and promotes waste treatment methods such as recycling and incineration with energy recovery. Hungary has implemented stringent measures to reduce the landfilling of industrial waste, focusing on reuse and recycling.
- **Industrial Emissions Directive (2010/75/EU)**
  The Industrial Emissions Directive regulates emissions from industrial activities, including waste processing and utilization. It ensures that waste recovery processes comply with environmental protection standards.
- **Packaging and Packaging Waste Directive (94/62/EC)**
  This directive aims to minimize packaging waste and encourage recycling and reuse. Hungary follows this directive to manage by-products from industrial packaging materials.

Hungary has enacted specific laws and policies to regulate the management and utilization of industrial wastes and by-products. These frameworks are designed to align with EU directives while addressing the country's unique industrial and environmental conditions.

- **Act CLXXXV of 2012 on Waste Management**
  This act serves as the cornerstone of Hungary's waste management legal framework. It establishes guidelines for waste classification, collection, treatment, and recovery. Encouraging waste prevention at the industrial level. Promoting the use of industrial by-products as secondary raw materials. Implementing extended producer responsibility (EPR) for industries generating significant waste streams.
- **Government Decree No. 246/2014 on Waste Recovery**
  This decree specifies conditions for waste recovery and the use of by-products in industrial processes. It supports the recycling of materials like metal scrap, construction waste, and fly ash from power plants.
- **Environmental Protection Act (Act LIII of 1995)**
  The Environmental Protection Act mandates that industrial waste utilization practices minimize environmental harm. It includes provisions for monitoring waste treatment facilities and enforcing compliance with environmental standards.
- **Tax on Environmental Product Charges**
  Hungary imposes taxes on products that generate waste, such as packaging and electronic equipment, to incentivize waste reduction and the use of recycled materials in industrial production.

In addition, Hungary's legal frameworks encourage the utilization of industrial by-products to support the circular economy.

Construction and demolition waste is one of the largest waste streams in Hungary. Regulations encourage its recycling into secondary aggregates for use in road construction and infrastructure projects.

By-products from thermal power plants and steel production, such as fly ash and slag, are used in cement manufacturing and soil stabilization. Government policies promote the safe handling and utilization of these materials.

Packaging waste, including plastics, paper, and metals, is subject to recycling targets under Hungary's implementation of the Packaging and Packaging Waste Directive. Recycled materials are used in industrial production processes to reduce reliance on virgin resources.

Organic industrial waste, such as food processing residues, is utilized for biogas production. Policies support waste-to-energy initiatives as part of Hungary's renewable energy strategy.

While challenges such as inadequate infrastructure and enforcement persist, strategies like strengthening regulations, investing in technology, and fostering public-private partnerships can drive progress. By prioritizing sustainable waste management, societies can mitigate the environmental impact of industrial activities and pave the way for a cleaner, healthier future.

Legal frameworks are essential for managing, disposing of, and sustainably utilizing agricultural wastes and by-products. By providing clear guidelines, enforcing compliance, and promoting innovation, these regulations can transform agricultural waste from an environmental burden into a valuable resource. However, challenges such as inadequate enforcement, fragmented regulations, and financial constraints must be addressed to ensure widespread adoption of sustainable practices. By strengthening legal frameworks and fostering collaboration between stakeholders, the agricultural sector can contribute to a cleaner, healthier, and more sustainable future.

9.
Management, Disposal, and Utilization of Agricultural Wastes and By-Products

Agricultural waste and by-products are the inevitable outcomes of agricultural activities that include crop production, livestock farming, aquaculture, and forestry. These materials, if not managed appropriately, can pose significant environmental, economic, and health challenges. However, with proper management strategies, agricultural waste can be transformed into valuable resources, contributing to sustainability, circular economy, and agricultural productivity.

Agricultural wastes refer to the residues generated during farming activities. By-products, on the other hand, are secondary products derived during agricultural production, such as molasses from sugarcane processing or straw from cereal crops. These materials vary widely in composition and potential applications, ranging from organic-rich residues to mineral-based by-products.

Types of Agricultural Waste:

- Crop residues include stalks, leaves, husks, shells, and other plant parts left after harvesting crops like wheat, rice, maize, and sugarcane.
- Animal Manure and Slurry: Generated in livestock farming, these contain organic matter, nitrogen, phosphorus, and other nutrients.
- Agro-industrial Waste: By-products of agricultural processing, such as oilseed cakes, bagasse (from sugarcane), and fruit pulp.
- Aquaculture Waste: Includes fish excreta, feed residues, and waterborne nutrients from aquaculture systems.
- Forestry Residues: Leftover wood chips, sawdust, and bark from forestry activities.

Unmanaged agricultural waste can lead to environmental pollution, greenhouse gas emissions, water contamination, and public health hazards. Addressing these issues involves adopting waste management strategies that promote recycling, energy recovery, and sustainable utilization. Effective management of agricultural waste requires integrated approaches encompassing collection, storage, processing, and treatment. Proper harvesting methods reduce the quantity of damaged or unusable produce, minimizing waste at the source. Optimizing the use of fertilizers, pesticides, and water reduces the generation of hazardous residues. Separating organic and inorganic waste ensures efficient downstream processing. Building well-designed storage facilities minimizes spoilage and leakage into the environment.

Treatment Methods:

- Composting: A biological process that converts organic waste into nutrient-rich compost, improving soil fertility and structure.
- Anaerobic Digestion: The decomposition of organic waste in oxygen-free environments produces biogas (methane) and digestate, which can be used as fertilizer.
- Incineration: Combustion of dry agricultural waste generates energy, though this process requires strict control to prevent air pollution.
- Chemical and Mechanical Treatments: Processes like pyrolysis, gasification, and pelletizing convert agricultural residues into energy products or feedstock.

Disposal methods are often chosen based on the type of waste, its volume, and local regulations. Sustainable disposal aims to minimize environmental impacts while recovering resources wherever possible. Applying organic waste directly to fields enriches soil with organic matter and nutrients.

Biochar, produced from the pyrolysis of biomass, improves soil structure, retains moisture, and sequesters carbon.

Landfilling remains a common practice for agricultural waste, especially for non-recyclable materials. However, it contributes to methane emissions and occupies valuable land resources.

Utilizing **animal manure** and other organic waste in anaerobic digesters produces biogas, a renewable energy source.

Agricultural residues like bagasse and straw can be incinerated to produce heat and electricity.

Improper disposal methods can contaminate soil, water, and air, contributing to ecological imbalances. High costs of advanced treatment technologies can limit their adoption in resource-poor regions. Inconsistent policies and lack of enforcement often hinder sustainable waste disposal.

The **utilization of agricultural waste** not only reduces environmental burden but also creates economic opportunities and supports sustainable practices. Organic waste processed through composting and vermiculture is widely used as an eco-friendly alternative to chemical fertilizers. Nutrient-rich effluents from anaerobic digestion can be used as liquid fertilizers. Biogas plants utilize organic agricultural waste to produce energy for cooking, heating, and electricity generation. Agro-industrial by-products like molasses and oilseed residues serve as feedstock for biofuel production. Compressed biomass from crop residues is used as fuel in industrial and domestic settings. By-products like oilseed cakes, bran, and pulp are processed into high-protein animal feed. Aquaculture waste can be repurposed as a component of fish feed, reducing reliance on wild-caught fishmeal. Starch from crop residues and lignin from forestry waste are used to produce biodegradable plastics and packaging materials. Agro-waste like jute and coir are used in textiles, while rice husk ash and bagasse are utilized in construction materials.

Advancements in technology have opened new frontiers for agricultural waste management and utilization. One effective approach involves using waste from one agricultural process becomes an input for another, ensuring resource efficiency and minimizing waste generation. Additionally, enzymes extract valuable compounds from agro-waste, such as pectin from citrus peels. Moreover, microbial fermentation produces biofuels, organic acids, and other biochemicals from agricultural residues.

Governments can promote waste treatment facilities through financial incentives.

Training farmers on waste management practices encourages community engagement and local solutions.

Sustainable management and utilization of agricultural waste offer several benefits:

- Proper handling of waste prevents water and air contamination, preserving ecosystems.
- Techniques like biochar application and anaerobic digestion reduce greenhouse gas emissions.
- Biogas and biofuels provide renewable energy alternatives, reducing dependence on fossil fuels.
- Waste valorization creates revenue streams for farmers and supports rural industries.

The management, disposal, and utilization of agricultural wastes and by-products are crucial for contributing to sustainable agriculture and mitigating environmental impacts. By embracing innovative technologies and promoting circular economy principles, agricultural waste can be transformed into valuable resources, benefiting both farmers and society. Policymakers, researchers, and agrarian practitioners must collaborate to ensure that waste management strategies are effective, economically viable, and environmentally friendly. Through collective efforts, agricultural waste can be turned from a liability into an asset, contributing to a more sustainable and resilient agricultural sector.

10.
The Process of Wastewater Treatment and the Use of the Generated Sewage Sludge and Compost in Plant Production

Water is one of the most critical resources on Earth, essential for life and development. As the human population grows and urbanization expands, the management of wastewater has become a pressing global concern. Wastewater treatment is a systematic process designed to remove contaminants from water, making it safe for reuse or release into the environment. A by-product of this process, sewage sludge, holds significant potential for use in agriculture. When processed into compost, it can serve as a sustainable resource for plant production.

10.1. The Process of Wastewater Treatment and Presentation of the Products Produced During the Process

Wastewater treatment involves a series of steps to purify water by removing physical, chemical, and biological impurities. These processes are typically divided into three stages: primary, secondary, and tertiary treatment.

The **primary treatment** focuses on removing large particles and solids from wastewater. The process begins with screening, where debris such as plastics, leaves, and other large items are filtered out. After screening, the wastewater flows into sedimentation tanks, where heavier solids settle at the bottom to form primary sludge. This stage reduces the bulk of suspended solids and organic materials in the water, preparing it for further treatment.

Secondary treatment targets the removal of dissolved organic matter and biological contaminants. This stage relies heavily on microbial activity to break down organic compounds. The wastewater is aerated to encourage the growth of aerobic microorganisms, which consume organic pollutants. The biological treatment can occur through various systems, such as activated sludge processes, trickling filters, or biological aerated filters. At the end of secondary treatment, a secondary sedimentation process separates the biomass (activated sludge) from the treated water. The clarified water is then sent for tertiary treatment, while the sludge is either recycled into the process or sent for further processing.

Tertiary treatment focuses on refining the water to meet specific quality standards, often for reuse or safe discharge into natural water bodies. Processes in this stage may include filtration, chemical treatment, and disinfection. Techniques such as reverse osmosis, UV treatment, or chlorination are employed to eliminate any remaining contaminants, including pathogens, heavy metals, and nutrients like nitrogen and phosphorus.

10.1.1. Products Produced During Wastewater Treatment

Throughout the wastewater treatment process, solid by-products, known as **sewage sludge**, are generated. This sludge consists of organic matter, nutrients, microorganisms, and varying levels of contaminants. For sewage sludge to be used in agriculture, it must undergo additional processing to stabilize it and reduce potential health risks. The transformation process involves stabilization, dewatering, and composting.

- Stabilization is a critical step in processing sewage sludge to reduce its pathogen load and odor while increasing its safety for agricultural use. Microorganisms break down organic material in the absence of oxygen, producing biogas (a renewable energy source) and stabilized sludge (anaerobic digestion).
- Organic material is decomposed in the presence of oxygen, resulting in reduced sludge volume and improved pathogen control (aerobic digestion). The addition of lime raises the sludge's pH, effectively neutralizing pathogens and odors (lime stabilization).
- Dewatering involves removing excess water from stabilized sludge to reduce its volume and facilitate transportation. Mechanical methods, such as centrifugation, belt presses, or filter presses, are commonly used to achieve this goal. The resulting semi-solid material, referred to as biosolids, can be further processed into compost.
- Composting converts sewage sludge into a nutrient-rich soil amendment by mixing it with carbon-rich materials such as straw, sawdust, or wood chips. The composting process involves controlled biological decomposition under aerobic conditions. The compost pile is monitored for temperature, moisture, and aeration to ensure optimal microbial activity. After several weeks to months, the process yields mature compost that is safe for agricultural use. The final product is free of pathogens, has a neutralized odor, and is rich in organic matter and nutrients beneficial for plant growth.
- It is is rich in essential plant nutrients, including nitrogen, phosphorus, and potassium. These nutrients are slowly released into the soil, providing a steady supply for crops. Additionally, the compost contains micronutrients like zinc, copper, and manganese, which are vital for plant health and development.
- The organic matter in sewage sludge compost enhances soil structure, water retention, and aeration. It promotes the aggregation of soil particles, reducing erosion and improving the soil's capacity to support root growth. Compost also increases the cation exchange capacity of soils, ensuring that plants can access essential nutrients.

- Using compost in agriculture contributes to carbon sequestration by incorporating stable organic matter into the soil. This practice mitigates climate change by reducing greenhouse gas emissions and improving soil resilience against extreme weather conditions.
- The application of sewage sludge compost reduces the dependence on chemical fertilizers and pesticides. This shift not only lowers agricultural costs but also minimizes the environmental impact associated with the production and use of synthetic inputs.

Sewage sludge compost serves as a sustainable alternative to synthetic fertilizers and improves soil health, fostering long-term agricultural productivity.

While the benefits of using sewage sludge compost in agriculture are significant, certain **challenges** must be addressed to ensure its safe and effective application.

- Sewage sludge may contain contaminants such as heavy metals, pharmaceuticals, and microplastics. These substances can pose risks to plant health, soil quality, and human consumers. To mitigate these risks, rigorous testing and treatment standards are essential.
- The use of sewage sludge in agriculture is regulated in many countries to protect public health and the environment. Farmers and producers must comply with guidelines regarding the application rates, treatment methods, and permissible contaminant levels.
- The idea of using treated sewage sludge in agriculture may face resistance from consumers due to concerns about safety and hygiene. Transparent communication and education are necessary to build trust and promote the adoption of this sustainable practice.

Alternative techniques like pyrolysis, anaerobic digestion, and coal co-combustion have drawn more interest recently. One promising method for waste reduction and resource recovery is pyrolysis, which transforms sludge into charcoal, gas, and oil while drastically lowering its volume and immobilizing dangerous substances.

Another option for sustainable municipal wastewater sludge management is the drying and bio-drying of municipal waste to raise its calorific value by lowering its humidity to about 15%. This method has fewer negative effects on the environment than other waste management technologies.

The treatment of wastewater is an essential process for safeguarding environmental and human health. The by-products of this process, particularly sewage sludge, represent a valuable resource when transformed into compost. Composting not only provides an eco-friendly solution to waste management but also enhances soil fertility, supports sustainable plant production, and contributes to climate change mitigation.

10.2. Utilization of Sewage Sludge and Compost in Agriculture

10.2.1. Agricultural Use of Sewage Sludge

Sewage sludge, a by-product of wastewater treatment processes, has emerged as a valuable resource in agricultural practices. Its application as a fertilizer or soil conditioner has sparked significant interest due to its potential to recycle nutrients and organic matter, reduce waste, and support sustainable agriculture. However, the use of sewage sludge in agriculture also poses challenges, such as contamination risks, regulatory hurdles, and public perception concerns.

Sewage sludge is the solid, semi-solid, or slurry residue produced during the treatment of municipal and industrial wastewater. Its composition varies depending on the source of wastewater and the treatment processes employed.

Typically, **sewage sludge contains**:

- Nutrients: Nitrogen, phosphorus, potassium, and trace elements such as zinc, copper, and magnesium are essential for plant growth.
- Organic Matter: Decomposed organic material that can improve soil structure, water retention, and aeration.
- Contaminants: Heavy metals (e.g., lead, cadmium, mercury), pathogens, pharmaceuticals, and microplastics, which pose environmental and health risks if not properly managed.

Understanding the composition of sewage sludge is critical for evaluating its suitability for agricultural use and ensuring its safe application.

One of the primary benefits of using sewage sludge in agriculture is its **ability to recycle nutrients**. Sewage sludge contains significant amounts of nitrogen and phosphorus, essential components of synthetic fertilizers. Applying treated sludge to farmland provides a valuable nutrient source for the soil, reducing reliance on chemical fertilizers and supporting circular economy principles.

The organic matter in sewage sludge helps **improve soil quality** by enhancing its structure, water-holding capacity, and fertility. This can be particularly beneficial in arid and semi-arid regions where soils are often depleted of organic material.

Using sewage sludge as a fertilizer is often more **cost-effective** than disposing of it in landfills or incinerating it. Farmers can benefit from reduced input costs, while municipalities save on waste management expenses.

Incorporating organic matter into the soil can contribute to **carbon sequestration**, a process that helps mitigate climate change by storing carbon in the soil instead of releasing it into the atmosphere.

Despite its benefits, the agricultural use of sewage sludge poses several **risks** that must be carefully managed.

Sewage sludge can contain **heavy metals** such as cadmium, lead, and mercury, which can accumulate in soil and enter the food chain. This poses risks to human health, animal health, and ecosystem integrity.

Pathogens such as bacteria, viruses, and parasites present in untreated sludge can pose serious health risks. While treatment processes can significantly reduce pathogen levels, residual risks remain if the sludge is not properly managed.

Emerging contaminants such as **organic pollutants**, pharmaceuticals, hormones, and microplastics are increasingly found in sewage sludge. These substances can have unknown and potentially long-term impacts on soil health, water quality, and biological systems.

Public resistance to the use of sewage sludge in agriculture stems from concerns about food safety and environmental contamination. Negative perceptions can limit the adoption of sludge-based fertilizers, despite evidence of their benefits.

To **mitigate risks** and maximize benefits, sewage sludge must undergo rigorous treatment and processing before agricultural application.

Common treatment methods include:

- Anaerobic digestion involves breaking down organic matter in the absence of oxygen, producing biogas as a by-product. This process stabilizes sludge, reduces pathogens, and minimizes odors.
- Composting mixes sewage sludge with organic materials such as straw or wood chips to create a stable, nutrient-rich product. The heat generated during composting helps kill pathogens and reduce odors.
- Thermal drying removes moisture from sewage sludge, reducing its volume and making it easier to transport and store. The resulting product is often pelletized for agricultural use.
- Adding lime to sewage sludge raises its pH, reducing pathogen levels and odors. Lime-stabilized sludge is commonly used as a soil conditioner.
- Emerging technologies such as pyrolysis, hydrothermal carbonization, and thermal hydrolysis are being explored to further enhance the safety and utility of sewage sludge for agriculture.
- The use of sewage sludge in agriculture is governed by strict regulations in many countries to protect public health and the environment. Key regulatory frameworks include:

The EU's Sewage Sludge Directive (86/278/EEC) sets limits on heavy metal concentrations, application rates, and soil monitoring requirements. Member states are encouraged to recycle sludge while safeguarding soil and water quality.

The EPA's Part 503 Rule establishes standards for the treatment, use, and disposal of sewage sludge, including pollutant limits, pathogen reduction requirements, and site restrictions.

Individual countries and regions have developed their guidelines tailored to local conditions and priorities. These frameworks often require testing and certification of sludge products before agricultural use.

To ensure the safe and effective use of sewage sludge in agriculture, best practices should be followed. Sewage sludge should be tested for nutrient content, heavy metals, pathogens, and other contaminants to ensure compliance with regulatory standards. Only adequately treated sludge should be applied to agricultural land. Treatment processes should be chosen based on the specific risks and requirements of the intended application. Sludge should be applied during the appropriate season to minimize nutrient runoff and maximize plant uptake. Injection or incorporation into the soil can reduce odors and nutrient losses. Crops with minimal direct contact with sludge, such as grains and forage crops, are preferred over those consumed raw, such as fruits and vegetables.

Denmark has successfully integrated sewage sludge into its agricultural sector by implementing strict regulations and promoting public-private partnerships. Treated sludge is widely used as a fertilizer, contributing to nutrient recycling and waste reduction.

Several U.S. cities, including Milwaukee, have developed successful biosolids programs. Milwaukee's "Milorganite" product, derived from treated sewage sludge, is a popular fertilizer used in agriculture, landscaping, and golf courses.

In India, treated sewage sludge is being utilized to improve soil fertility in organic farming systems. Pilot projects have demonstrated significant yield improvements and cost savings for smallholder farmers.

Sewage sludge represents a valuable yet underutilized resource for agriculture. By recycling nutrients and organic matter, it can support sustainable farming practices while reducing waste and environmental impacts. However, its use must be carefully managed to address risks associated with contaminants, pathogens, and public perception. Through rigorous treatment, strict regulatory oversight, and the adoption of best practices, sewage sludge can play a pivotal role in advancing sustainable agriculture and resource management. Continued innovation, research, and stakeholder engagement will be key to unlocking its full potential.

10.2.2. Agricultural Use of Compost

Compost, a nutrient-rich material derived from the controlled decomposition of organic matter, has become a cornerstone of sustainable agriculture. Its ability to improve soil fertility, enhance water retention, and promote ecological balance makes it a critical tool for farmers seeking to reduce chemical inputs and improve yields. With global concerns over soil degradation, climate change, and food security, the use of compost in agriculture offers an environmentally friendly solution to some of the most pressing challenges in modern farming.

Compost is created through the aerobic decomposition of organic materials such as plant residues, food waste, animal manure, and other biodegradable substances. Microorganisms, including bacteria and fungi, play a crucial role in breaking down these materials into a stable, humus-like product. The quality and composition of compost depend on the source materials and the composting process.

Compost is a source of essential plant nutrients, including nitrogen (N), phosphorus (P), potassium (K), and micronutrients like calcium, magnesium, and sulfur. Its high organic content improves soil structure, enhancing aeration, water infiltration, and microbial activity.

Compost contains diverse microbial populations that promote nutrient cycling and suppress soil-borne diseases. The balanced composition of compost makes it an ideal soil amendment for sustainable agricultural practices.

One of the most significant benefits of compost is its ability to **enhance soil health**. Organic matter in compost improves soil structure, increases porosity, and boosts the soil's capacity to retain moisture and nutrients. This is particularly valuable in regions prone to drought or where soil degradation has reduced productivity.

Compost acts as a **slow-release fertilizer**, providing plants with a steady supply of nutrients over time. Unlike synthetic fertilizers, which can cause nutrient leaching, compost binds nutrients in organic forms that are less prone to runoff, reducing water pollution.

Incorporating compost into the soil helps **store carbon**, reducing greenhouse gas emissions and mitigating climate change. The organic matter in compost contributes to the formation of stable carbon compounds that remain in the soil for decades.

Compost fosters a diverse and **active microbial community**, which is essential for nutrient cycling, disease suppression, and the breakdown of organic matter. Healthy microbial populations also support plant growth by enhancing root function. Compost can suppress soil-borne pathogens and pests by **promoting beneficial microorganisms** that outcompete harmful ones. This natural form of disease control reduces the need for chemical pesticides.

Composting provides a sustainable method for managing organic waste, reducing the amount of material sent to landfills, and recovering valuable nutrients that would otherwise be lost.

The versatility of compost makes it suitable for a wide range of agricultural practices. Compost is commonly used to improve soil fertility and structure. It can be applied as a top dressing, mixed into the soil, or incorporated during planting to ensure even distribution. As a mulch, compost helps conserve soil moisture, regulate temperature, and suppress weeds. Mulching with compost is particularly beneficial for perennial crops, orchards, and vineyards.

Compost tea, a liquid extract of compost, is used as a foliar spray or soil drench to enhance plant health and suppress diseases. It is a popular choice for organic farmers seeking natural alternatives to synthetic treatments. Compost is effective in stabilizing soil and preventing erosion on slopes, construction sites, and degraded lands. Its application helps bind soil particles and promotes the growth of vegetation. In degraded or contaminated soils, compost can restore fertility and improve physical properties. It is often used in mine reclamation, urban green spaces, and degraded agricultural lands.

While compost offers numerous benefits, its use in agriculture is not without **challenges**:

The quality of compost can vary widely depending on the source materials and composting process. Poor-quality compost may contain contaminants, weed seeds, or pathogens that can harm crops. Compost is typically low in readily available nitrogen compared to synthetic fertilizers. Farmers may need to supplement with other nutrient sources to meet crop demands. Producing or purchasing compost can be labor-intensive and costly, particularly for large-scale farms. Transportation costs can also be significant, especially if compost must be hauled over long distances. The composting process can take several weeks to months, depending on the method used. This may not align with immediate farming needs. Compost made from municipal waste or improperly sorted materials may contain heavy metals, plastics, or chemical residues that pose risks to soil health and food safety. Despite its benefits, compost use remains underutilized in many regions due to a lack of awareness, training, and access to high-quality compost.

To maximize the benefits and minimize the risks associated with compost use, farmers should follow **best practices**:

- Using clean, uncontaminated organic materials is essential for producing high-quality compost. Avoiding materials with heavy metals, chemicals, or pathogens ensures a safe end product.
- Farmers should adopt effective composting techniques, such as windrows, aerated static piles, or in-vessel systems, to achieve thorough decomposition and pathogen reduction. Monitoring temperature, moisture, and oxygen levels is critical for successful composting.
- Regular testing for nutrient content, pH, and contaminants ensures that compost meets quality standards. Testing helps farmers tailor compost application rates to specific crop and soil needs.
- Applying compost at the right time and in appropriate quantities is crucial for maximizing nutrient availability and minimizing losses. For most crops, applying compost before planting or during soil preparation is ideal.
- Compost should be integrated with other sustainable practices, such as crop rotation, cover cropping, and integrated pest management, to achieve holistic soil and crop health.

In California's organic farming sector, compost is widely used to improve soil fertility and comply with organic certification standards. Research has shown that compost applications increase crop yields, enhance soil carbon storage, and reduce greenhouse gas emissions.

In India, smallholder farmers use compost made from crop residues and animal manure to reduce dependency on costly synthetic fertilizers. Community composting initiatives have helped improve soil health and increase food security in rural areas.

European vineyards, particularly in France and Italy, use compost to improve soil structure and support healthy grapevine growth. Compost applications have been linked to higher grape quality and improved wine production.

In Kenya, composting programs have been implemented to address soil degradation and nutrient depletion. Farmers using compost have reported improved yields and reduced input costs, contributing to food security and poverty alleviation.

Advances in composting technologies, such as microbial inoculants and biochar integration, are improving the speed and quality of compost production. These innovations make composting more efficient for large-scale operations. Urban composting initiatives are gaining momentum, converting food waste into valuable compost for urban agriculture and community gardens. These programs address waste management challenges while promoting local food systems. Combining compost use with precision agriculture tools, such as soil sensors and nutrient mapping, allows farmers to optimize application rates and improve efficiency. Governments and organizations are increasingly recognizing the importance of compost in sustainable agriculture. Policies that incentivize compost use, such as subsidies, tax breaks, and certification programs, can drive wider adoption.

The agricultural use of compost offers a sustainable and effective solution to many of the challenges facing modern farming. By enhancing soil health, recycling nutrients, and reducing waste, compost supports the transition to regenerative and climate-resilient agriculture. However, its adoption requires careful management, quality assurance, and integration with other practices to address potential challenges. With continued innovation, education, and policy support, compost has the potential to play a pivotal role in achieving global food security and environmental sustainability.

10.2.3. Legal regulation about the agricultural use of wastewater, sewage sludge, and sewage sludge compost in Hungary

The **Government Decree No. 50/2001** (IV. 3.) outlines the legal framework for the safe and sustainable use of wastewater and sewage sludge in Hungarian agriculture. This regulation aims to ensure environmental protection, food safety, and soil quality while promoting the beneficial recycling of organic matter and nutrients from these materials. Strict limits are set for the concentration of heavy metals, pathogens, and organic pollutants in both wastewater and sewage sludge. Compliance with these standards is mandatory to minimize risks to human health and the environment (Table 3-4). This decree supports sustainable agriculture by promoting the recycling of valuable nutrients like nitrogen and phosphorus while reducing reliance on synthetic fertilizers. Properly treated sludge also enhances soil structure and organic matter content.

Table 3: Limit values for toxic elements and harmful substances permitted in wastewater for agricultural use in Hungary based on Government Decree No. 50/2001 (IV. 3.) Own editing

Parameter	Limit values (mg/l)
Al	10.0
As	0.2
B	0.7
Ba	4.0
Cd	0.02
Co	0.05
ΣCr	2.5
Cr VI.	0.5
Cu	2.0
Fe	20.0
Hg	0.01
Mn	5.0

Parameter	Limit values (mg/l)
Mo	0.02
Ni	1.0
Pb	1.0
Zn	5.0
Cl-	150
Animal and vegetable fats (organic solvent extract)	200
Anionic surfactant	30
ΣPAH	1.0 mg/mg dry matter
ΣPCB	0.1 mg/kg dry matter
TPH	30

Table 4. The limit values of toxic elements and harmful substances that can be applied to agricultural land with wastewater, sewage sludge and sewage sludge compost in Hungary based on Government Decree No. 50/2001 (IV. 3.) Own editing

Parameter	Limit value (kg/ha/year)
As	0.5
Cd	0.15
Co	0.5
ΣCr	10
Cu	10
Hg	0.1
Mo	0.2
Ni	2.0
Pb	10
Se	1.0
Zn	30
ΣPAH	0.1
ΣPCB	0.05
TPH	40

Despite the challenges of contaminants and public perception, advancements in treatment technologies and regulatory frameworks ensure that sewage sludge compost can be safely integrated into agriculture. By embracing these practices, society can move closer to a circular economy where waste is transformed into a resource, fostering environmental sustainability and agricultural resilience.

The Government Decree No. 50/2001 (IV. 3.) establishes comprehensive regulations for the agricultural use and management of wastewater and sewage sludge in Hungary. Paragraph 4 (1) of the decree specifically outlines the limit values for various elements and organic pollutants to ensure environmental safety and protect public health (Table 5).

The decree sets maximum allowable concentrations for potentially harmful substances in both wastewater and sewage sludge intended for agricultural use. These limits are crucial to prevent excessive accumulation of toxic elements in soil and crops, which could pose risks to ecosystems, livestock, and human health.

Table 5: Limit values for agricultural use of sewages sludge and sewage sludge compost in Hungary based on Government Decree No. 50/2001 (IV. 3.) Paragraph 4 (1) Own editing

Parameter	Sewage sludge limit values mg/kg dry matter	Sewages sludge compost mg/kg dry matter
As	75	25
Cd	10	5
Co	50	50
ΣCr	1000	350
Cr VI.	1	1
Cu	1000	750
Hg	10	5
Mo	20	10
Ni	200	100
Pb	750	400
Se	100	50
Zn	2500	2000
ΣPAH	10	5
ΣPCB	1	0.5
TPH	4000	1000

Parameter	Sewage sludge limit values mg/kg dry matter	Sewages sludge compost mg/kg dry matter
Microbiological limits		
Human parasitic roundworm egg count	–	25 g negative
Salmonella sp.	–	2×5 g negative
Faecal coliform	–	500/g
Faecal streptococcus		500/g

Farmers intending to apply sewage sludge must obtain official approval. Sludge application is permitted only on designated land types where contamination risks are minimal. Application rates are calculated based on the nutrient content of the sludge, ensuring optimal fertilization without overloading the soil.

In addition, the **59/2008. (IV. 29.) FVM Decree** establishes detailed regulations in Hungary to protect water resources from nitrate pollution originating from agricultural activities. This decree aligns with the **European Union's Nitrate Directive** (91/676/EEC), which aims to minimize the risk of nitrate contamination in surface and groundwater caused by excessive nitrogen application.

The decree outlines specific rules for the agricultural use of wastewater, sewage sludge, and sewage sludge compost to ensure environmental protection and sustainable farming practices. These rules are designed to mitigate the risk of nitrate leaching and water contamination.

Wastewater, sewage sludge, and sewage sludge compost may only be applied to agricultural land under controlled conditions to prevent nitrate pollution. These materials must undergo appropriate treatment and stabilization to reduce pathogenic risks and minimize environmental impact. The application must adhere to defined nutrient balance principles, ensuring that nitrogen levels align with crop nutrient demands to prevent excessive nitrate accumulation.

The decree specifies the maximum permissible nitrogen load from organic fertilizers, including wastewater and sewage sludge. The **limit for nitrogen application** is set at **170 kg N/ha/year** on nitrate-sensitive zones, in accordance with EU guidelines. The nitrogen content in sewage sludge and its potential release into the soil must be carefully calculated to avoid over-application. The application of wastewater, sewage sludge, or compost is prohibited near water bodies, wells, and drainage systems to reduce the risk of water pollution. Strict buffer zones must be maintained around environmentally sensitive areas. Prior to application, soil testing is mandatory to assess nutrient levels and ensure the suitability of the field.

Farmers and land managers must provide detailed records of the type, quantity, and timing of sewage sludge or wastewater application. Authorities conduct regular inspections and sampling to verify compliance with nitrate protection measures. Entities involved in the application of wastewater, sewage sludge, or compost must register their activities with relevant authorities.

Comprehensive data on the source, composition, and application methods must be submitted as part of the data provision requirements. These records contribute to ongoing monitoring programs designed to track nitrate levels in soil and water.

The 59/2008. (IV. 29.) FVM Decree establishes essential safeguards for the responsible use of wastewater, sewage sludge, and composted sewage sludge in Hungarian agriculture. By setting clear limits, monitoring standards, and registration requirements, the decree effectively reduces the risk of nitrate pollution while encouraging sustainable nutrient recycling practices

10.3. The Effect of Sewage Sludge and Compost on Photosynthesis

Photosynthesis is a critical biological process through which plants convert light energy into chemical energy, the foundation of most terrestrial ecosystems and agricultural productivity. Soil quality, nutrient availability, and environmental conditions significantly influence the efficiency of photosynthesis. Two commonly used soil amendments, sewage sludge, and compost, play a pivotal role in modifying these factors. Both materials enhance soil fertility, but their chemical composition, nutrient release patterns, and potential contaminants create differing effects on plant growth and photosynthesis.

Photosynthesis occurs in plant chloroplasts and involves the conversion of carbon dioxide and water into glucose and oxygen, driven by sunlight. The process can be summarized by the equation.

Photosynthesis efficiency is influenced by several factors:

- Nutrient Availability: Essential elements like nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and trace elements are crucial for synthesizing chlorophyll, enzymes, and energy molecules (ATP).
- Soil Water Retention: Adequate moisture availability ensures the steady uptake of water for photosynthesis and nutrient transport.
- Soil Structure and Aeration: Optimal soil structure facilitates root growth and gas exchange, allowing efficient uptake of CO_2 and nutrients.

Sewage sludge and compost influence these factors differently, shaping their impact on photosynthesis.

Sewage sludge is a by-product of wastewater treatment, rich in organic matter, nutrients, and trace elements. Its composition can significantly enhance or inhibit photosynthesis, depending on the quality of the sludge and its application.

Sewage sludge is rich in nitrogen, phosphorus, and trace elements such as zinc and copper, which are essential nutrients.

Nitrogen for instance, is a critical component of chlorophyll and amino acids, vital for plant growth and development. Therefore, sewage sludge applications can improve chlorophyll synthesis, enhancing light absorption and photosynthetic efficiency.

Phosphorus is vital for ATP synthesis and energy transfer. Therefore, phosphorus in sewage sludge supports energy production in plants, which is central to the photosynthesis process. The organic matter in sewage sludge improves soil structure, increasing its water-holding capacity. Improved moisture availability supports photosynthesis by ensuring the steady uptake of water and dissolved nutrients.

While sewage sludge and compost offer benefits, their potential contaminants can negatively impact photosynthesis. Contaminants such as cadmium, lead, and mercury can disrupt photosynthetic enzymes, reduce chlorophyll production, and impair plant metabolic processes. Residual pathogens and pharmaceuticals in untreated or poorly treated sludge can inhibit root function, indirectly reducing nutrient uptake and photosynthetic rates. Improper application can lead to soil acidification or alkalization, disrupting nutrient availability and photosynthesis.

Studies have shown that applying treated sewage sludge and compost to crops like maize and wheat can increase chlorophyll content and photosynthetic rates under controlled conditions. However, excessive application has been linked to heavy metal accumulation in soil and plants, reducing photosynthesis and overall plant health.

Sewage sludge and compost are valuable tools for enhancing soil fertility and supporting photosynthesis. Compost, with its balanced nutrient release and absence of harmful contaminants, offers a safer and more sustainable solution for improving photosynthesis and agricultural productivity. Sewage sludge, while nutrient-rich, poses risks that must be carefully managed through advanced treatment and regulated application. By understanding the distinct effects of these soil amendments, farmers and policymakers can make informed decisions to optimize plant growth, sustain ecosystems, and ensure long-term agricultural productivity.

Research on the combined effects of sewage sludge and beneficial bacteria on plant photosynthesis is scarce. Few studies have examined the beneficial effects of applying sewage sludge on the photosynthetic activity of specific plant species, including sunflower, maize, and *Medicago sativa*. Increased radiation use efficiency in CO_2 assimilation, along with stimulation of the coefficient of photochemical quenching and transpiration, are the main factors contributing to the favorable influence on photosynthetic activity.

In a basil experiment, the results indicated that while the treatments had no discernible effect on the amount of chlorophyll-a in the leaves, the amount of chlorophyll-b and carotenoids was significantly higher in basil leaves grown on sewage sludge and sewage sludge amended substrates than in basil grown on eroded soil. The presence of important metal ions and the high concentration of accessible N and P in sewage sludge, which are ingredients necessary for chlorophyll production, may be the cause of the rise in assimilatory pigment content in basil leaves grown on sewage sludge and sewage sludge-amended substrates. Metal toxicity at high quantities may be the cause of some species' decreased chlorophyll levels when cultivated on sewage sludge. Since N is a component of the structure of chlorophyll molecules, it has been demonstrated that N levels and the amount of chlorophyll in leaves are positively correlated for several species. In the thylakoid lumen of chloroplasts, carotenoids function as free radical quenchers, contributing significantly to antioxidant activity. Sewage sludge has been shown to have beneficial impacts on plant growth, which supports its usage as an organic fertilizer and soil supplement. However, there have also been worries raised over the potential toxicity of sewage sludge.

Chlorophyll fluorescence is one metric that may be used to evaluate the effectiveness of the photosystem II and, consequently, the photosynthetic capability of plants. Application of sewage sludge also reflects potential harmful influences on the photosynthesis efficiency parameters. The use of sewage sludge amendments was shown to affect parameters like Fv/Fm and FPSII (maximum quantum yield of PSII and actual quantum yield of PSII), indicating probable harmful consequences.

10.4. Balancing the Benefits and the Risks of Sewage Sludge and Sewage Sludge Compost

The increasing global demand for sustainable agriculture has emphasized the need for effective nutrient recycling and soil improvement practices. Sewage sludge and sewage sludge compost, by-products of wastewater treatment, have gained attention for their potential to enhance soil fertility and promote plant growth. These organic amendments are rich in nutrients such as nitrogen (N), phosphorus (P), and trace elements, which can significantly influence plant nutrient uptake. However, their application in agriculture involves balancing benefits with risks, including heavy metal contamination, pathogens, and nutrient imbalances.

Sewage sludge is rich in macronutrients and trace elements, making it a valuable source of nutrients for plant growth. Its effects on nutrient uptake are influenced by its composition, application rates, and treatment methods. Sewage sludge supplies essential nutrients in readily available forms. These nutrients are present in high concentrations in sewage sludge. When applied to soil, they are released gradually, providing a steady supply for plant uptake. Elements like zinc, copper, and iron enhance enzymatic activities and metabolic pathways, promoting healthy growth. The organic matter in sewage sludge improves soil structure, aeration, and water-holding capacity. Enhanced soil properties facilitate root penetration and nutrient absorption.

Heavy metals in sewage sludge can accumulate in the soil, interfering with nutrient uptake. For example: Cadmium competes with essential nutrients like zinc and calcium for uptake.

Lead forms insoluble complexes, reducing phosphorus availability.

High nutrient concentrations in sewage sludge may lead to:

- Nutrient Antagonism: Excess nitrogen can inhibit potassium uptake, leading to imbalances.
- Over-application Risks: Excess phosphorus can reduce zinc and copper uptake, disrupting plant metabolism.

A study on corn crops treated with sewage sludge showed increased nitrogen and phosphorus uptake, resulting in higher biomass yields. However, elevated cadmium levels in the soil reduced zinc uptake, highlighting the importance of balanced application rates.

In a study on tomato plants, sewage sludge compost significantly increased nitrogen and phosphorus uptake compared to untreated soil. The compost-treated soil also showed higher microbial activity and reduced heavy metal uptake, indicating its suitability for long-term agricultural use.

Sewage sludge and sewage sludge compost have distinct impacts on plant nutrient uptake. Their comparative effects are summarized in Table 1.

Table 1: Effects of sewage sludge and compost on plant physiology processes

Aspect	Sewage sludge	Compost
Nutrient availability	High nutrient levels, raid release.	Moderate nutrient levels, slow, sustained release.
Impact on chlorophyll	Significant improvement, but the risk of heavy metals inhabitation.	Gradual improvement with no toxic effect.
Organic matter content	High, improves soil water retention.	High, enhances soil structure, and microbial activity
Contaminant risks	Heavy metals, pathogens, and pharmaceuticals.	Minimal, provided source materials are clean.
Microbial interactions	Limited or suppressed due to contaminants.	Promotes beneficial microbial activity.
Sustainability	Limited by contamination concerns.	Highly sustainable and eco-friendly.

Source: own editing

10.5. The Effect of Sewage Sludge and Compost on the Physiological, Morphological, and Biochemical Parameters of Plants

When applied to plants, sewage sludge, and compost, especially when properly composted, can have a significant impact on their physiological, morphological, and biochemical parameters by improving soil structure, boosting microbial activity, and providing essential nutrients like phosphorus and nitrogen. This generally results in increased plant growth and yield, but improper treatment may raise concerns about contaminant levels. Careful management is required to prevent potential problems with heavy metals and pathogens found in untreated sewage sludge.

Plants produce **antioxidant enzymes** to protect themselves from oxidative stress caused by reactive oxygen species (ROS). When plants are exposed to heavy metals or other pollutants present in sewage sludge, the production of ROS often increases. This leads to oxidative stress, which triggers a response from the plant's antioxidant defense system. Antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), play a critical role in protecting plants from oxidative stress by neutralizing reactive oxygen species generated under stress conditions.

Sewage sludge affects antioxidant enzyme activity in maize due to heavy metals, organic pollutants, and its nutrient-rich composition. Low levels of metal stress can enhance enzyme activity, while high concentrations may overwhelm the plant's defenses, causing enzyme inhibition or oxidative damage. The impact depends on the sludge's composition, metal content, and concentration. Studies on spinach and wheat have shown that sewage sludge application increased SOD, CAT, and POD activities, indicating an enhanced antioxidant defense mechanism in response to the stress induced by heavy metals. In other crops like tomato and maize, sludge containing higher concentrations of heavy metals was found to cause oxidative stress, leading to the overproduction of ROS and increased enzyme activities, though in some cases, enzyme inhibition was observed due to severe metal toxicity. In addition, the organic matter and nutrients in sewage sludge may enhance plant growth, which can increase metabolic processes, leading to the production of more ROS. The antioxidant enzymes act to balance these ROS levels, preventing oxidative damage.

Plants exposed to moderate levels of sewage sludge over time may develop a degree of tolerance, maintaining high antioxidant enzyme activity as an adaptive mechanism to long-term metal exposure. Properly treated sewage sludge with lower levels of contaminants may stimulate the antioxidant defense system without causing harmful levels of stress, leading to a balanced increase in enzyme activity that supports better growth and stress resistance in maize.

Sludge that has not been adequately treated or contains high levels of toxic compounds can lead to excessive stress on maize, overwhelming its antioxidant defenses and causing negative impacts on enzyme activity and overall plant health.

When applied to plants, sewage sludge, and compost can significantly influence their morphological parameters by promoting increased plant height, larger leaf size, greater biomass production, and a higher number of branches, primarily due to the readily available nutrients like nitrogen and phosphorus they provide, which are crucial for plant growth and development, while also improving soil structure and water retention capacity; however, careful consideration must be given to potential heavy metal contamination within the sewage sludge depending on its treatment process.

Increased application of sewage sludge or compost can often lead to taller plants compared to untreated controls. Plants grown with sewage sludge or compost may exhibit larger leaves due to increased nutrient availability. Stems of plants treated with sewage sludge or compost might be thicker and stronger. Increased branching can be observed in plants receiving sewage sludge or compost applications, leading to a bushier appearance. Improved soil structure due to compost or sewage sludge can lead to more extensive and robust root systems.

10.6. Case study: Presentation of the results of an experiment with sewage sludge

For many years, sewage sludge has been widely used on arable land. Although there is a limit to the quantity of sewage sludge that can be spread to arable land, this by-product, when processed as trash, can contribute vital nutrients to the soil. In essence, the sludge's composition dictates whether or not it can be applied. The experiment aimed to show that increasing sewage sludge concentrations (25%, 50%, and 75%, m/m) affects the physiological, morphological, and biochemical characteristics of maize. A glasshouse was used to set up the experiment. Plant height, relative chlorophyll content, photosynthetic pigments (carotenoids, chlorophyll-a, and chlorophyll-b), leaf proline and malondialdehyde (MDA) content, and PS II quantum efficiency in the three-leaf were measured. Lower dosages of sewage sludge had a positive impact on maize's early growth. In comparison to the control, the relative chlorophyll content in each treatment was noticeably increased. The PS II reaction centers' maximum quantum efficiency did not significantly vary between the treatments. The MDA and proline content of maize leaves were affected differently in this experiment by varying amounts of sewage sludge treatments. All treatments had significantly greater proline contents, but there was no discernible difference in MDA content when compared to the control.

The test plant was maize (*Zea mays L.* cv. Armagnac). Four treatments (0%, 25%, 50%, and 75% sewage sludge based on mass) were applied with seven plants per treatment (one plant per pot) in three replicates. Maize plants were planted in PVC tubes. The volume of the experimental pots was 750 ml, each pot contained 500 g soil as the control or soil and sewage sludge mixtures as the three applied treatments. Three seeds per tube were sown, and one week after planting only well-developed maize plants were separated. Temperatures for growth varied between 32 °C (daytime) and 25 °C (night), the humidity was kept above 40% (45–55%) during the experiment.

The dewatered sewage sludge came from a sewage treatment plant in Debrecen, Hungary. The main parameters of sewage sludge are presented in Table 6.

The used soil originated from Karcagpuszta, Hungary (N 47.25154; E 20.83351). The soil type is poor-quality saline soil (K3).

Table 6. The heavy metal content of sewage sludge

Element	Element content (mg/kg dry material)	Element content concerning the permitted limit (%)
Cd	0.85	8.5
Co	4.44	8.88
Cr	50.43	5
Cu	181.04	18.1
Hg	0.63	6.3

Element	Element content (mg/kg dry material)	Element content concerning the permitted limit (%)
Mo	6.3	31.5
Ni	22.14	11
Pb	19.2	2.5
Se	1.5	1.5
Zn	1500.6	60

Values are means (n = 3) Source: Own data

In terms of plant height, the 25% sewage sludge treatment resulted in plants that were 15% taller than the control plants. For the other treatments, there were no statistically significant differences.

The amount of photosynthetic pigments also were measured. It can be seen (Table 7) that the 50% sewage sludge treatment had a significantly higher value relative to the control, whereas 25% and 75% sludge treatments had no effects. Plants planted in 50% SS had significantly higher levels of photosynthetic pigments compared to the control. The increase was 26% for chlorophyll-a, 81% for chlorophyll-b, and 26% for carotenoids. Furthermore, the highest treatment effect (75% sludge) was around the control except for chlorophyll-b, where it was almost 5% lower. The application of sludge (vermicomposted) caused a significant increase in the chlorophyll content of beans relative to the control soil. The chlorophyll content in sugar beet leaf increased when 10% and 25% concentrations of SS treatment were applied, while the 50% concentration did not induce an increase.

However, none of the applied treatments had effects on the maximum quantum efficiency of the PS II reaction center among the treatments.

Table 7. The impacts of different sewage sludge treatments (25%; 50%; 75%) on the chlorophyll a,b, and carotenoid content (mg g^{-1}) in the third leaf of maize

Treatments	Chlorophyll-a	Chlorophyll-b	Carotenoids
Control	16.75 ± 1.80	5.27 ± 1.28	8.18 ± 0.87
25% sludge	17.93 ± 3.74	5.97 ± 2.25	8.52 ± 1.49
50% sludge	21.14 ± 1.49*	9.55 ± 1.90*	10.35 ± 0.30*
75% sludge	17.32 ± 1.59	5.05 ± 1.25	8.19 ± 0.63

Values are mean (n = 3) ± S.E. *Source:* Own data

Malondialdehyde is the outcome of lipid peroxidation. It can be found in cells naturally and the increased amount of MDA indicated the oxidative stress condition. The extent of lipid peroxidation and the amount of MDA are influenced by various stress factors. Proline is a so-called stress amino acid that accumulates in response to physiological stress. The proline content was notably higher in 25%, 50%, and 75% of sludge treatments relative to the non-treated plants.

However, the amount of MDA did not change significantly compared to the values measured in control plants. It can be concluded that the applied sewage sludge treatments stressed the plants but did not affect all parameters. The MDA content of lettuce significantly increased when the solid by-product of wastewater treatment (2.5%, 5%, and 7.5%) was used in comparison with the control. However, they did not find any significant difference between the 2.5 and 5% treatments. Proline content was also notably higher in the 7.5% SS-treated plants, while no significant difference was observed between 2.5 and 5% SS treatments. There was no significant difference among the three (2.5%, 5%, and 7.5%) treatments when the maximum leaf conductance was measured. It was stated that the elevated proline content is an indicator of stress sensitivity with no clear correlation with higher antioxidant activity. In addition, a slightly positive correlation between MDA and proline content also were observed. On the other hand, the higher proline content may reduce the MDA content which can reduce the unwanted impacts of stress.

The results showed that the lower dose of sewage sludge treatment (25% and 50%) had positive effects on the initial growth of the plants. In addition, all the applied treatments increased the relative chlorophyll content of maize. However, the proline content also indicates that all treatments stressed the plants. However, the nature and extent of the stress are not yet clear. There was no significant difference among treatments in the maximum quantum efficiency of the PSII reaction centers concerning the applied sewage sludge. It can be said that the sludge used has a content value that makes it suitable for agricultural use.

11.
Biogas Production and the Usage of the Generated By-Products

Biogas production is the process of generating a renewable energy source through the anaerobic digestion of organic matter, such as agricultural waste, animal manure, food waste, or sewage. This process produces biogas, a mixture of gases, primarily methane (CH_4) and carbon dioxide (CO_2), and a nutrient-rich byproduct called digestate, which can be used as a fertilizer.

Countries around the world have demonstrated the potential of biogas production to address energy and environmental challenges. In Germany, a robust policy framework and financial incentives have supported the development of over 9,000 biogas plants, making the country a global leader in biogas production. These plants contribute significantly to the renewable energy mix and provide heat and power to millions of households.

India and China have also made significant strides in promoting biogas production, particularly in rural areas. National programs have supported the installation of millions of small-scale biogas plants, providing clean energy to rural households and improving waste management. These initiatives have improved living standards while reducing reliance on traditional biomass fuels.

11.1. The Importance of Biogas Production

Biogas production has emerged as a transformative solution to the growing global challenges of energy security, environmental degradation, and sustainable development. Derived from organic materials such as agricultural residues, food waste, and sewage, biogas represents a renewable and versatile energy source that offers multiple environmental, economic, and social benefits. This chapter explores the importance of biogas production, examining its role in energy generation, waste management, climate change mitigation, and rural development while addressing the challenges associated with its adoption and implementation.

Biogas is a **renewable energy source** that addresses the pressing need to transition away from fossil fuels. Its primary component, methane (CH_4), can be used for electricity generation, heating, and as a substitute for natural gas. Unlike non-renewable resources such as coal and oil, biogas production is sustainable because it relies on readily available organic waste materials, which are replenished continuously through natural and human activities.

The global energy demand continues to rise, placing immense pressure on conventional energy systems and increasing greenhouse gas emissions. Biogas production offers a sustainable alternative by converting organic waste into usable energy. This process not only provides a clean energy source but also reduces the carbon footprint associated with traditional energy production. Furthermore, biogas plants can be integrated into local energy grids, ensuring energy accessibility for communities in remote and underdeveloped regions.

One of the most significant advantages of biogas production is its ability to **manage organic waste effectively**. Organic waste, including food scraps, agricultural residues, and animal manure, often ends up in landfills or is left to decompose in open fields. This leads to the release of methane, a potent greenhouse gas that contributes to global warming. By diverting organic waste to anaerobic digesters, biogas production prevents uncontrolled methane emissions and reduces the burden on landfills.

In urban areas, food waste constitutes a major portion of municipal solid waste. Establishing biogas plants in cities can help manage this waste efficiently, reducing landfill space requirements and associated environmental issues such as leachate contamination and odor. In rural areas, where agricultural and animal waste is abundant, biogas production offers a practical solution for managing these resources while providing energy for local use.

Climate change is one of the most pressing global challenges, and biogas production plays a crucial role in mitigating its effects. Methane capture through anaerobic digestion prevents this potent greenhouse gases (GHG) from escaping into the atmosphere, significantly reducing overall emissions. Additionally, biogas production displaces the use of fossil fuels, which are major contributors to carbon dioxide (CO_2) emissions.

The **digestate**, a byproduct of biogas production, serves as a nutrient-rich organic fertilizer. Its use in agriculture reduces the dependency on synthetic fertilizers, which require significant energy inputs for production and contribute to nitrous oxide emissions when applied excessively. Thus, biogas production not only addresses energy and waste issues but also supports sustainable agricultural practices.

Biogas production has profound implications for **rural development**, particularly in developing countries where energy generation and waste management are significant challenges. Small-scale biogas plants can provide rural households with a reliable and affordable energy source, reducing reliance on traditional fuels such as firewood and charcoal. This shift has multiple benefits, including reduced indoor air pollution, decreased deforestation, and improved health outcomes.

In addition to providing energy, biogas production creates economic opportunities in rural areas. Farmers can monetize agricultural residues and manure by supplying them to biogas plants or using biogas technology on their farms. The digestate produced can be sold as a high-quality organic fertilizer, generating additional income streams. Moreover, biogas projects often involve the construction, operation, and maintenance of plants, creating jobs, and fostering skill development within local communities.

11.2. History of Biogas Production

Examining the contributions of various cultures and scientific advancements to its evolution helps address modern challenges such as climate change and energy security. Tracing its historical trajectory highlights key milestones that have established biogas as a cornerstone of renewable energy strategies worldwide.

The roots of biogas production can be traced back to **ancient civilizations** that observed the natural decomposition of organic materials. Although early humans lacked the scientific understanding we have today, they recognized the practical benefits of gases produced by decaying matter.

In the first century AD, Roman naturalist Pliny the Elder documented the existence of flammable gases emanating from decomposing organic waste. These observations, though rudimentary, marked humanity's initial encounter with the principles of anaerobic digestion. Similar knowledge existed in ancient China and India, where organic matter, such as animal dung, was often collected and utilized for heating purposes.

In Persia, around the 10th century, anaerobic processes were employed to manage human and animal waste, converting them into fertilizers and other resources. While biogas as an energy source was not explicitly harnessed during these periods, these practices laid the groundwork for future developments.

The scientific foundation for biogas production began to take shape in the **17th century**. Jan Baptista Van Helmont, a Flemish chemist and physician, identified gases produced by decomposing organic materials, though he did not isolate methane specifically. These early studies marked the beginning of a systematic understanding of biogas.

In **1776**, Italian physicist Alessandro Volta made a groundbreaking contribution to biogas research. While exploring swamp gases, Volta observed the flammability of methane and its connection to decomposing organic matter. His experiments provided the first clear link between biological decomposition and combustible gases, offering a glimpse into the energy potential of biogas.

By the early **19th century**, Humphrey Davy, a British chemist, expanded upon Volta's findings. Davy's experiments in 1808 demonstrated that methane could be extracted from manure, setting the stage for the practical application of anaerobic digestion. This period represented the convergence of curiosity and science, advancing biogas from mere observation to a subject of focused research.

The 19th century witnessed the emergence of biogas as a practical energy source. Rapid urbanization and the accompanying challenges of waste management created a pressing need for innovative solutions. Biogas production began to take on a formal structure, with early digesters designed to process organic waste while generating usable energy.

In 1859, the first known anaerobic digester was built in Bombay, India, to treat human waste. This small-scale system not only improved sanitation but also highlighted biogas's potential as an energy source. Across Europe, similar efforts were underway.

In 1895, Exeter, England, constructed a municipal anaerobic digester to produce biogas for street lighting. This marked a pivotal moment in biogas history, demonstrating its scalability and practicality.

These early industrial systems laid the foundation for modern biogas technologies, proving that biogas could address both environmental and energy needs.

The **20th century** marked a period of rapid advancement in biogas production, driven by global events, technological innovation, and growing energy demands.

During World War I and II, energy shortages prompted nations to explore alternative energy sources, including biogas. Small-scale anaerobic digesters were deployed in rural areas to provide fuel for heating and cooking. European farms, in particular, embraced biogas systems, recognizing their ability to convert agricultural waste into energy.

The mid-20th century saw biogas systems gaining traction in developing countries. In India, the Khadi and Village Industries Commission promoted biogas plants in rural areas to address energy scarcity and improve sanitation. China, too, launched extensive biogas programs, constructing millions of household digesters. These efforts were supported by international organizations like the Food and Agriculture Organization (FAO) and the United Nations Development Programme (UNDP), which recognized biogas's potential to alleviate poverty and improve living conditions.

During the 1960s and 1970s, biogas research experienced global expansion. Scientists explored the potential of co-digestion, where multiple types of organic waste were processed together to increase methane yield. This period also saw the development of more efficient digester designs, laying the groundwork for large-scale waste-to-energy projects.

The 1970s oil crises marked a turning point for renewable energy, including biogas. With fossil fuel prices soaring, governments and researchers intensified efforts to develop sustainable alternatives. Biogas emerged as a viable solution, attracting investments in anaerobic digestion technologies.

In Europe, large-scale digesters were built to process municipal solid waste, agricultural residues, and industrial by-products. Countries like Germany and Sweden led the way, integrating biogas into their renewable energy portfolios. Advanced technologies, such as temperature-controlled digesters and biogas upgrading systems, significantly improved efficiency and output.

The **late 20th century** also saw biogas gaining recognition as a tool for climate change mitigation. Methane capture from organic waste not only produced energy but also reduced greenhouse gas emissions, aligning with global sustainability goals. Biogas plants became central to waste management strategies, particularly in urban areas.

Today, biogas systems are more sophisticated than ever. Innovations in biogas upgrading allow methane to be purified and injected into natural gas grids or used as vehicle fuel. Co-digestion techniques enhance energy production, while circular economy models integrate biogas with agriculture, aquaculture, and wastewater treatment. These advancements demonstrate biogas's adaptability and lasting relevance.

The history of biogas offers valuable lessons for its future development. First, the importance of continuous research and innovation is evident in biogas's evolution from rudimentary systems to advanced technologies. Second, adapting biogas systems to local resources and needs has proven critical for their success, particularly in rural and developing regions.

Looking forward, biogas production is poised to play an even greater role in global energy systems. Emerging trends include the integration of biogas with hydrogen production and, expanding its applications in industries and transportation. Additionally, biogas's potential to support circular economies, where waste becomes a resource, positions it as a key driver of sustainable development.

As global efforts to combat climate change intensify, biogas stands out as a versatile and scalable solution. Its ability to reduce emissions, manage waste, and provide renewable energy aligns with the goals of a low-carbon future.

11.3. The Process of Biogas Production

Anaerobic digestion, the process by which microorganisms break down organic materials (plant and animal products) without oxygen, produces biogas. Anaerobic digestion is used in biogas systems to recycle this organic waste into biogas, which contains valuable soil products (solids and liquids) as well as energy (gas).

An anaerobic digester can optimize, control, and contain anaerobic digestion, which is already present in nature, landfills, and some livestock waste management systems. About 50–70% methane, 30–40% carbon dioxide, and trace amounts of other gases are present in biogas. Digestate, the liquid and solid digested material, is commonly applied as a soil amendment.

In a digester, some organic wastes are harder to break down than others. Livestock manure is typically the most challenging to decompose, but food waste, fats, oils, and greases are the easiest organic wastes to do so. Co-digestion, or combining several wastes in one digester, can assist boost biogas production. Wastes can also decompose more quickly in digesters that are warmer, usually maintained between 30 and 38 degrees Celsius.

Once captured, biogas can provide power and heat for use in fuel cells, engines, and microturbines. Additionally, biogas can be converted into biomethane, often known as renewable natural gas, and then either used as vehicle fuel or injected into natural gas pipelines.

Biogas production involves several stages and processes, primarily centered on anaerobic digestion, where microorganisms break down organic materials in the absence of oxygen. Below is a detailed overview of the process:

1. Feedstock Preparation

- Selection: Various organic materials can serve as feedstocks, including agricultural residues (crop wastes, manure), municipal solid waste (food scraps, yard waste), sewage sludge, and energy crops (maize, energy grasses).
- Preparation: Feedstocks may require preprocessing, such as shredding or grinding, to increase surface area and facilitate digestion.

2. Anaerobic Digestion

- Digestion Tank: The prepared feedstock is introduced into a sealed anaerobic digester tank, which can be of various types (batch, continuous, plug-flow) depending on the scale anddesign.
- Microbial Action: Anaerobic bacteria break down complex organic molecules (carbohydrates, proteins, lipids) in the feedstock, releasing methane (CH_4) and carbon dioxide (CO_2) as byproducts.
- Optimal Conditions: Temperature and pH levels are maintained to optimize microbial activity. Mesophilic digestion typically operates at around 35-40°C, while thermophilic digestion operates at higher temperatures (50-60°C), each having different microbial populations and digestion rates.

3. Gas Collection and Storage

- Gas Production: Methane produced during digestion rises to the top of the digester, displacing the digesting slurry.
- Collection: The biogas (methane and CO_2 mixture) is collected from the digester's headspace using a gas dome or roof and piped to a storage facility or directly to utilization equipment.
- Gas Composition: Biogas typically consists of 50-70% methane (CH_4) and 30–50% carbon dioxide (CO_2), along with trace amounts of other gases like hydrogen sulfide (H_2S) and water vapor.

4. Gas Utilization

- Energy Conversion: Biogas can be used directly for heating applications (boilers, space heating) or converted into electricity and heat through combined heat and power (CHP) systems.
- Biomethane: Biogas can be upgraded through purification processes (e.g., pressure swing adsorption or water scrubbing) to produce biomethane, which meets natural gas quality standards and can be injected into natural gas grids or used as a vehicle fuel.

5. Digestate Management

- Residue: The solid and liquid remnants of the digestion process, called digestate, are rich in nutrients and organic matter.
- Separation: Digestate may undergo separation to produce solid and liquid fractions.
- Use: The solid fraction can be used as organic fertilizer, while the liquid fraction can be recycled back into the digestion process or used as nutrient-rich irrigation water for crops.

6. Monitoring and Control

   Continuous monitoring of temperature, pH, gas production rates, and composition ensures optimal process conditions and efficiency.

11.4. Biogas production in agriculture

The agricultural sector generates a wide variety of organic wastes, making it an ideal setting for biogas production. Common materials used as feedstocks for biogas production include animal manure and crop residues.

On average, a dairy cow weighing 1,000 pounds produces 80 pounds of dung every day. Before being spread on fields, this manure is frequently kept in holding tanks. As the manure breaks down, it not only releases methane but also has the potential to add to the overabundance of nutrients in streams. Only 3% of livestock waste is recycled using anaerobic digesters, even though managing livestock manure accounted for almost 10% of all methane emissions in the US in 2015. Anaerobic digestion can minimize greenhouse gas emissions, smells, and up to 99 percent of manure pathogens when using livestock waste to produce biogas. An estimated 8,241 animal biogas systems may provide more than 13 million megawatt-hours of electricity annually, according to EPA calculations.

Plant trimmings, stalks, and straws are examples of crop wastes. To preserve soil moisture and organic matter and to stop erosion, some leftovers are left on the field. On the other hand, higher crop yields result in more residues. In such cases, it may be sustainable to remove these residies for other uses. The crop cultivated, the kind of soil, and the climate all affect sustainable harvest rates. According to the U.S. Department of Energy, there are currently about 104 million tons of crop residues available for $60 per dry ton, accounting for sustainable harvest rates. Due to the high lignin content that hinders their breakdown, crop leftovers are typically co-digested with other organic waste. Co-digestion with manure improves methane yields and optimizes the digestion process.

Wastes from food processing industries, such as fruit and vegetable peels, dairy waste, and brewery residues, are valuable feedstocks. These materials often have high energy potential due to their organic composition. Every year, almost 30% of the world's food supply is lost or squandered. Approximately 133 billion pounds (66.5 million tons) of food waste were created in the US in 2010 alone, mostly from the commercial and home food industries. Source reduction is given top priority in EPA's Food Recovery Hierarchy to solve this waste, followed by the use of excess food to alleviate hunger; animal feed and energy generation are given lower priority. As a last option, food should be disposed of in landfills. Regretfully, only 5% of food waste is recycled into fertilizer or soil improver, although accounting for 21% of landfills in the United States. The majority of this trash is dumped in landfills, where it decomposes and releases methane. Although biogas may be captured by landfills, organic waste disposal does not allow for the recycling of nutrients from the organic material. The EPA and USDA established targets in 2015 to cut the quantity of food waste that ends up in landfills by half by 2030. However, there will still be extra food that needs to be recycled even if this objective is accomplished. There is a substantial energy potential. Anaerobic digestion, for instance, can provide enough energy annually to power 800–1,400 households with 100 tons of food waste every day. To boost the generation of biogas, fat, oil, and grease gathered from the food service sector can also be added to an anaerobic digester.

In some cases, dedicated energy crops, such as maize silage or grass, are cultivated specifically for biogas production. While effective, this practice raises questions about land use and competition with food crops.

Biogas production in agriculture offers a multitude of environmental, economic, and social benefits, making it a cornerstone of sustainable farming practices.

Biogas systems provide an effective way to manage agricultural waste, reducing the need for traditional disposal methods such as landfilling or incineration.

Proper waste treatment minimizes the risk of water and soil pollution from manure runoff. Biogas can be used to generate electricity, heat, or as vehicle fuel, reducing reliance on non-renewable energy sources.

Farms with biogas systems can achieve energy self-sufficiency, lowering operational costs.

Capturing methane from organic waste prevents its release into the atmosphere, significantly reducing greenhouse gas emissions.

Digestate, a by-product of biogas production, serves as a low-carbon alternative to synthetic fertilizers. It also enhances soil fertility by providing essential nutrients like nitrogen, phosphorus, and potassium.

Unlike raw manure, digestate is stabilized and free from pathogens, improving its safety and usability. Farmers can diversify their income by selling surplus energy or biofertilizers.

Biogas production creates jobs in rural areas, from plant construction to maintenance and operation.

Several countries and regions have demonstrated the successful integration of biogas into agriculture, serving as models for wider adoption.

As a global leader in biogas production, Germany has over 9,000 biogas plants, many of which are farm-based.

Policies like feed-in tariffs and subsidies have encouraged farmers to invest in anaerobic digesters, contributing to the country's renewable energy goals.

India's National Biogas and Manure Management Programme has supported the installation of millions of small-scale biogas plants in rural areas.

These plants provide clean energy for cooking and lighting while improving waste management.

China has implemented large-scale biogas programs, particularly in rural areas, to address energy poverty and waste management challenges.

The country's focus on household digesters has benefited millions of smallholder farmers.

Denmark has pioneered the use of co-digestion, combining animal manure with industrial and household organic waste to maximize biogas output.

Centralized biogas plants serve multiple farms, promoting collaboration and efficiency.

11.5. Advantages and Disadvantages of Biogas Plants

Biogas plants provide a range of **benefits**, from waste management and energy production to environmental conservation and economic growth.

Biogas plants generate renewable energy from organic waste, reducing reliance on fossil fuels. Biogas production utilizes resources such as manure, crop residues, and municipal solid waste, which are continually replenished. Biogas can be used for electricity, heat, or as a vehicle fuel in its upgraded form (biomethane). Small-scale biogas plants empower rural households and communities to generate their energy, reducing dependency on external energy supplies.

Biogas plants offer an effective solution for **managing organic waste**. Biogas plants process agricultural residues, food waste, and sewage, preventing their accumulation in landfills Anaerobic digestion reduces the risk of water and soil contamination caused by untreated waste runoff. In rural areas, biogas plants linked to toilets improve hygiene and sanitation by converting human waste into energy.

Biogas plants contribute to **climate change mitigation** by capturing methane, a potent greenhouse gas, and using it as a renewable energy source. Methane captured from organic waste is used for energy, preventing its release into the atmosphere. Biogas production displaces fossil fuels, reducing net carbon dioxide emissions. The nutrient-rich digestate reduces the need for synthetic fertilizers, which are energy-intensive to produce and contribute to nitrous oxide emissions.

Biogas plants promote a circular **economy** by converting waste into valuable resources.

The by-product of anaerobic digestion, digestate, is used as an organic fertilizer, returning nutrients to the soil. Biogas plants recycle organic waste into energy and fertilizers, reducing the need for raw materials. Combining different feedstocks, such as animal manure and food waste, improves biogas yields and optimizes resource use.

Biogas plants can create **economic opportunities** and **reduce energy costs**. Farmers can sell surplus biogas or biomethane and market digestate as a biofertilizer. The construction, operation, and maintenance of biogas plants generate employment in rural and urban areas. Biogas provides a **low-cost alternative** to fossil fuels, reducing energy expenses for households and industries. Biogas plants enhance energy security by producing local energy and reducing dependence on imported fuels. Small-scale biogas plants support energy access in remote areas where grid connectivity is limited. Biogas plants operate continuously, providing a steady energy source irrespective of weather conditions, unlike solar or wind energy.

Despite its numerous benefits, biogas production faces several **challenges** that hinder its widespread adoption. One major barrier is the **high initial investment** required for constructing biogas plants, which can be prohibitive for small-scale farmers and low-income communities. Access to financing and government incentives is crucial to overcoming this hurdle.

Another challenge is the **efficient management of feedstock**. Biogas production relies on a consistent and high-quality supply of organic materials, which can be difficult to ensure in certain regions. Seasonal variations in agricultural residues, logistical challenges in waste collection, and competition for feedstock use are some of the factors affecting feedstock availability.

Technical challenges also pose a barrier to biogas adoption. Anaerobic digestion is a complex biological process that requires careful monitoring and maintenance to ensure optimal performance. Lack of technical expertise and inadequate infrastructure can lead to operational inefficiencies and reduced biogas yields.

To realize the full potential of biogas production, supportive policies and technological advancements are essential. Governments can play a pivotal role by providing subsidies, tax incentives, and low-interest loans to encourage investment in biogas projects. Regulatory frameworks that mandate organic waste segregation and landfill diversion can also drive feedstock availability for biogas plants.

Technological innovations are critical for improving the efficiency and scalability of biogas systems. Advances in anaerobic digestion technology, such as the development of high-rate digesters and co-digestion techniques, can enhance biogas yields and reduce costs. Additionally, biogas upgrading technologies that produce biomethane of natural gas quality can expand the range of applications, including injection into natural gas grids and use as vehicle fuel.

11.6. Possibilities of Utilization of Main and By-Products Generated During Biogas Production

The effective utilization of both the main product (biogas) and by-products (such as digestate, biochar, and surplus heat) is critical for enhancing the sustainability and economic viability of biogas plants.

Biogas itself is the primary product of anaerobic digestion and has versatile applications, primarily as an energy source.

Biogas can be utilized as a renewable energy source in multiple forms. Biogas can fuel gas engines or turbines to generate electricity. The produced electricity can be fed into power grids or used locally for industrial and residential purposes. When burned, biogas releases heat, which can be used for space heating, water heating, or industrial processes. Combined heat and power systems improve energy efficiency by simultaneously generating electricity and utilizing the waste heat for other purposes.

Upgrading biogas involves removing impurities like CO_2, hydrogen sulfide (H_2S), and water vapor, resulting in biomethane - a purified form of methane. Biomethane has applications similar to natural gas. Compressed biomethane can be used as vehicle fuel, providing an alternative to fossil fuels with significantly lower greenhouse gas emissions. Biomethane can be injected into natural gas pipelines for distribution, expanding its usability for heating and electricity. Biogas is used in industries as a clean fuel for boilers and kilns. It can replace fossil fuels, reducing carbon emissions and contributing to decarbonization efforts.

Anaerobic digestion produces several by-products that offer immense opportunities for utilization across various sectors. **Digestate**, a residual material left after biogas extraction and is rich in nutrients such as nitrogen, phosphorus, and potassium. It can be applied directly to agricultural fields as a natural fertilizer, improving soil fertility and reducing reliance on chemical fertilizers.

Its organic matter content enhances soil structure, increases water retention, and promotes microbial activity. Liquid digestate can serve as a nutrient solution in soilless agricultural systems. Digestate can be used as a growing medium in nurseries and landscaping projects, replacing peat and reducing environmental degradation caused by peat extraction. It also can be processed into value-added products such as biochar, compost, or pellets for easier handling and enhanced applications.

Biochar, when integrated with digestate or derived from the feedstock used in anaerobic digestion, holds significant promise. Biochar's stable carbon structure helps sequester carbon in soils for long periods, mitigating climate change. It improves soil aeration, water retention, and nutrient availability, complementing the benefits of digestate in agricultural applications. In addition, biochar can adsorb heavy metals and pollutants, making it suitable for environmental remediation efforts.

The anaerobic digestion process, especially in combined heat and power systems, generates excess **heat**. The surplus heat can be supplied to district heating systems, providing energy for residential and commercial heating. Industries requiring low-grade heat, such as food processing or greenhouse heating, can utilize this energy. Heat can be used to dry digestate or other agricultural products, facilitating storage and transportation.

Biogas contains significant amounts of **CO_2**, which can be captured during the upgrading process. CO_2 can be used in greenhouses to enhance plant growth and productivity. Food-grade CO_2 can be supplied to the beverage industry for carbonation or the preservation of packaged foods. Captured CO_2 can be used in chemical processes, refrigeration, or as a raw material for producing synthetic fuels and polymers.

The anaerobic digestion process concentrates nutrients in the by-products, offering opportunities for **nutrient recovery and recycling**. Phosphorus can be extracted from digestate in the form of struvite, a valuable slow-release fertilizer. Ammonia stripping and absorption techniques can recover nitrogen from liquid digestate, producing ammonium sulfate or nitrate fertilizers.

11.7. The Effect of the Digestate on Plant Physiology

Digestate, the nutrient-rich by-product of anaerobic digestion, has gained attention for its potential as a sustainable alternative to chemical fertilizers. With its high concentrations of nitrogen, phosphorus, potassium, and organic matter, digestate can improve soil fertility and stimulate plant growth. However, its effects on plants are multifaceted and depend on factors such as application methods, digestate composition, and plant species.

Digestate impacts **nutrient uptake** by providing a balanced supply of macro- and micronutrients in bioavailable forms. It contains nitrogen primarily as ammonium, which can be nitrified in soil to nitrate, ensuring steady nitrogen availability. Plants exhibit improved nitrogen uptake and utilization, leading to better growth and yield. Bioavailable phosphorus in digestate supports root development and energy transfer in plants. Digestate also provides essential trace elements like zinc, copper, and iron, which support enzymatic activities and metabolic pathways. However, excess nitrogen or other nutrients can suppress the uptake of secondary nutrients like magnesium. Improper application may lead to nutrient losses and environmental contamination.

Digestate influences several physiological processes, including photosynthesis, water use efficiency, and stress responses.

Nitrogen in digestate promotes **chlorophyll synthesis**, improving photosynthetic efficiency. Adequate potassium levels enhance stomatal regulation, facilitating better CO_2 uptake and water conservation. Potassium and organic matter in digestate **improve water uptake** and retention, enabling plants to perform better under drought conditions.

Digestate components help plants withstand drought, salinity, and temperature extremes by stabilizing cellular structures and osmotic balance. Nutrient availability from digestate supports the activity of antioxidant enzymes, reducing reactive oxygen species (ROS) damage.

Digestate application significantly affects **plant morphology**, including root and shoot development, plant height, and biomass accumulation. Phosphorus in digestate stimulates root elongation and branching, improving nutrient and water uptake. Organic matter enhances soil aeration and structure, facilitating root penetration. Digestate provides essential nutrients that promote vegetative growth and leaf expansion. Larger leaf areas increase light interception and photosynthetic capacity. Plants treated with digestate often exhibit higher biomass accumulation in roots, stems, and leaves due to enhanced nutrient availability.

Digestate influences plant **biochemical pathways**, impacting metabolite synthesis, enzymatic activity, and stress-related compounds. Increased nitrogen availability supports the synthesis of amino acids, proteins, and nucleic acids. Also, it enhances the production of phenolics, flavonoids, and alkaloids, enhancing stress tolerance and defense mechanisms. Its application enhances the activity of antioxidant enzymes, reduces oxidative stress, and neutralizes ROS, protecting cellular components. Osmoprotectants like proline and soluble sugars accumulate in plants treated with digestate, improving osmotic adjustment under stress conditions.

Studies on wheat and maize show increased germination rates, improved nutrient uptake, and higher yields with digestate application. Research on lettuce and spinach highlights improved leaf quality and reduced nitrate accumulation when digestate is used as a fertilizer. Experiments with salt-stressed crops demonstrate that digestate mitigates stress effects by enhancing osmotic balance and antioxidant defenses. Long-term application of digestate improves soil organic matter content, microbial activity, and nutrient cycling.

11.8. Case study: Presentation of the results of an experiment with the by-product of a biogas factory

A fluid by-product from biogas production in Biharnagybajom (Eastern Hungary) was studied for its plant physiological effects. While environmental protection is the main focus of sustainable development, agriculture also needs to carefully consider its components. Reducing the use of industrial chemicals while allowing producers to maintain the same level of output is one of the most significant goals for sustainable agriculture. Utilizing biogas factory wastes is one way to reduce the amount of used chemicals in agriculture. Large quantities of nutrients are taken up from soils by crop plants. Nutrients must be added to the extracted minerals that plants harvest to achieve the same yield, both in terms of quality and quantity. Fluid by-products can be a good material to replace industrial chemicals because they contain several essential elements.

The experiment was conducted using sunflower and maize seedlings. The experiment was conducted in a climate chamber under controlled environmental conditions (photon flux 300 µmol $m^{-2}s^{-1}$, temperature 25/20°C (day/night), humidity 65-75%, length of day and night 16h/8h). To grow the plants the following nutrient solution was used: 2.0 mM $Ca(NO_3)_2$, 0.7 mM K_2SO_4, 0.5 mM $MgSO_4$, 0.1 mM KH_2PO_4, 0.1 mM KCl, 10 µM H_3BO_3, 1 µM $MnSO_4$, 1 µM $ZnSO_4$, 0.2 µM $CuSO_4$, 0.01 µM$(NH_4)_6Mo_7O_{24}$. The plants received iron in the form of 100 µM Fe(III)-EDTA. The nutrient solution was changed every two days, and the aeration of the nutrient solution was continuous. The pH of the nutrient solution was 4.95. The plants were grown in 1.7 L plastic containers, 170 ml of the nutrient solution was diluted to 1.7 L, and various amounts of by-products (5, 10, and 50 ml/liter) were added. Eight treatments (Table 8) were applied in three replication, on pot contained 4 plants.

Table 8: The applied treatments during the experiment

Treatments	
negative control (no nutrient solution)	1
positive control (full nutrient solution)	2
full nutrient solution + 5 ml by-product	3
full nutrient solution + 10 ml by-product	4
full nutrient solution + 50 ml by-product	5
full nutrient solution + 5 ml by-product + biofertilizer	6
full nutrient solution + 10 ml by-product + biofertilizer	7
full nutrient solution + 50 ml by-product + biofertilizer	8

The used biofertilizer was a viscous liquid containing two bacteria, *Azotobacter chrococcum* (1–2x10^9 cm^{-3}) and *Bacillus megatherium* (1–2x10^8 cm^{-3}). The bacteria-containing biofertilizer was added to the nutrient solution at a concentration of 1 ml dm^{-3}.

The different parameters were measured 11 days for maize and 15 days for sunflower after putting the seedling to the nutrient solution. At this time, both maize and sunflower were in the 4-leaf state.

The relative chlorophyll contents of the second and third leaves, the elements contents of the shoots and root, and the dry weight of shoot and roots were measured.

The digestate produced as a by-product containe essential elements in significant concentrations for plants (Table 9). The concentration of the measured elements was close to optimal, showing its significance in nutrient supplementation in plants. Its significance is enhanced by the fact that it can be a matter of recycling a by-product, so its role in environmental protection is also significant. Based on the plant physiological tests of the biogas plant by-product used in different concentrations, can be concluded that the effect of the by-products used in different concentrations was different on the two test plants.

Table 9: The concentration (mg kg^{-1}) of the elements in the used by-product

Element	mg kg^{-1}	Element	mg kg^{-1}	Element	mg kg^{-1}
Al	109	**B**	3.19	**Ca**	1,411
Cu	3.89	**Fe**	157	**K**	2,651
Mg	433	**Mn**	14.6	**Na**	454
P	448	**S**	405	**Zn**	18.8

Values are mean (n = 3) *Source:* Own data

When examining the element content of the maize shoot, the Ca concentration was the highest in the positive control plant (2). The treatments reduced shoot K content compared to the positive control. The amount of Mg, except in the nutrient solution+ 10ml by-product + 1 ml biofertilizer treatment (7), increased as a result of the treatments, however, the amount of Mg in the shoots of maize grown in distilled water (1) was higher than in the positive control. The concentration of P increased at nutrient solution + 10 ml by-product (4) and nutrient solution+ 10ml by-product + 1 ml biofertilizer treatment (7), while all treatments increased the amount of S in the shoot.

There was a higher amount of S in the maize roots compared to the shoots of the positive control plants (2). All treatments increased the root Ca, P, and S content compared to the controls (1, 2). The amount of Ca was 2 times higher at the nutrient solution + 10 ml by-product treatment (4) than in the positive control (2). The amount of phosphorus was 2 times higher at the nutrient solution + 5 ml by-product + 1 ml biofertilizer treatment (6) compared to the control (2). As a result of the nutrient solution + 5 ml by-product (3) and nutrient solution + 5 ml by-product + 1 ml biofertilizer treatment (6) treatments, the K and Mg content also increased in the maize roots.

Table 10: Concentrations of the examined elements (Ca, K, Mg, P, and S) in the shoots and roots of maize (mg kg^{-1})

Elements	Treatments							
	Element content in the shoots of maize (mg kg^{-1})							
	1	2	3	4	5	6	7	8
Ca	1,010	6,842	5,689	6,071	3,541	5,938	5,124	3,644
K	8,493	77,070	58,265	62,382	45,159	64,617	72,206	43,588
Mg	2,585	1,958	2,149	2,429	2,210	2,255	1,703	2,242
P	7,237	16,410	14,721	16,764	10,766	15,049	18,887	10,038
S	1,875	3,059	3,416	4,016	3,903	4,102	3,559	4,108
Elements	Element content in the root of maize (mg kg^{-1})							
	1	2	3	4	5	6	7	8
Ca	604	3,584	5,982	7,189	5,555	5,239	4,641	5,521
K	7,125	19,078	30,306	13,418	8,341	37,377	17,622	12,286
Mg	404	1,814	2,374	1,577	1,154	2,598	1,691	1,701
P	2,776	3,897	6,794	5,229	5,079	8,001	4,950	6,081
S	1,426	4,058	7,151	5,375	5,951	7,551	5,916	7,933

Values are mean (n = 3)
(1: distilled water, 2: control, 3: nutrient solution + 5 ml by-product, 4: nutrient solution + 10 ml by-product, 5: nutrient solution + 50 ml by-product, 6: nutrient solution + 5 ml by-product + 1 ml biofertilizer, 7: nutrient solution+ 10ml by-product + 1 ml biofertilizer, 8: nutrient solution + 50 ml by-product + 1ml biofertilizer)
Source: Own data

Table 11: Concentrations of the examined elements (Ca, K, Mg, P, and S) in the shoots and roots of sunflower (mg kg^{-1})

Elements	Treatments							
	Element content in the shoots of sunflower (mg kg^{-1})							
	1	2	3	4	5	6	7	8
Ca	18,262	29,761	27,339	20,796	16,132	18,742	25,006	31,448
K	6,590	56,250	61,923	55,799	50,353	54,399	60,847	59,059
Mg	2,774	3,827	3,545	3,361	4,300	4,435	3,907	4,347
P	2,917	6,954	9,595	8,765	7,999	9,003	9,040	9,726
S	2,448	5,257	6,739	6,512	8,458	9,314	8,245	6,740

Elements	Element content in the root of sunflower (mg kg^{-1})							
	1	2	3	4	5	6	7	8
Ca	4,558	5,450	3,478	2,962	5,517	2,474	3,084	6,758
K	5,311	79,977	44,120	49,022	22,218	12,577	25,628	56,099
Mg	394	1,203	981	1,001	1,428	690	997	1,921
P	2,809	9,484	9,273	10,742	9,131	4,532	8,764	14,906
S	2,322	4,609	5,736	6,680	7,243	3,880	6,432	11,941

Values are mean (n = 3)
(1: distilled water, 2: control, 3: nutrient solution + 5 ml by-product, 4: nutrient solution + 10 ml by-product, 5: nutrient solution + 50 ml by-product, 6: nutrient solution + 5 ml by-product + 1 ml biofertilizer, 7: nutrient solution+ 10ml by-product + 1 ml biofertilizer, 8: nutrient solution + 50 ml by-product + 1ml biofertilizer)
Source: Own data

The measured elements were in higher concentration in the shoots of sunflowers than in maize. The amounts of P and K increased in all treatments, while the amount of Mg increased only in the treatments 5, 6, 7, and 8. Treatments 3, 7, and 8 also had a favorable effect on the amount of K, and treatment 8 had a favorable effect on Ca.

The amount of S in the roots of the sunflower was about 1.45 times higher at the treatment 4. This value was 1.5 times higher at treatment 5 and 2.5 times higher at treatment 8 compared to the control root. The concentration of P and Mg increased 1.5 times in treatment 8 compared to the control. The concentration of K decreased in all treatments compared to the control. The concentration of Ca decreased compared to the control, except for treatment 8.

The accumulation of organic matter by plants is a set of complex biochemical processes. The difference between photosynthesis and respiration gives the mass of organic matter, which means the biological yield at the end of a vegetation period. A part of this is the "economic crop", which is used for various purposes. Environmental factors determine the intensity of both processes, while the ultrastructure of the plant and its activity are the conditions for environmental effects to prevail.

The shoot dry weight was the highest at treatment 7 and lowest at control. At treatment 6, the dry weight of shoots and roots was significantly reduced. The decrease in shoot length was the smallest in treatment 7, but the other treatments significantly reduced the length of maize shoots (Table 12).

Table 12: Dry weight of shoots and roots of maize (g plant $^{-1}$) and length of shoots (cm)

Treatments	Shoot dry weight (g plant^{-1})	Root dry weight (g plant^{-1})	Shoot length (cm)
1	0.043 ± 0.01	0.035 ± 0.01	12.65 ± 1.96
2	0.120 ± 0.04	0.035 ± 0.01	23.17 ± 4.89
3	0.091 ± 0.02	0.021 ± 0.01***	19.43 ± 3.42*

Treatments	Shoot dry weight (g plant^{-1})	Root dry weight (g plant^{-1})	Shoot length (cm)
4	0.082 ± 0.02*	0.020 ± 0.01	19.35 ± 1.93*
5	0.096 ± 0.02	0.015 ± 0.00***	19.70 ± 1.58*
6	0.075 ± 0.02**	0.016 ± 0.00***	18.13 ± 2.14**
7	0.125 ± 0.03	0.027 ± 0.01	21.81 ± 3.21
8	0.084 ± 0.03*	0.013 ± 0.01***	18.02 ± 4.21**

Values are mean (n = 12) ± S.E.
Significant differences compared to the control: **p<0.01; ***p<0.001. (1: distilled water, 2: control, 3: nutrient solution + 5 ml by-product, 4: nutrient solution + 10 ml by-product, 5: nutrient solution+ 50 ml by-product, 6: nutrient solution + 5 ml by-product + 1 ml biofertilizer, 7: nutrient solution+ 10 ml by-product + 1 ml biofertilizer, 8: nutrient solution + 50 ml by-product + 1 ml biofertilizer)
Source: Own data

Except for treatment 5, the dry weight of sunflower shoots increased. As a result of the treatment 3, the shoots dry weight increased by 18%. This value was 30% for treatment 4 and 34% for treatment 6. In treatments 7 and 8, the increase was smaller. Treatment 7 increased the dry weight by 17% and treatment 8 by 7%. These increases were significant. Treatments 3, 4, and 6 had a favorable effect on the dry weight of the root. As a result of treatment 3, the sunflower dry weight increased by 2%, in treatment 4 by 4%, and by 1% in treatment 6. While, treatments 5, 7, and 8 significantly reduced the dry weight of sunflower roots.

Table 13: Dry weight of shoots and roots of sunflower

Treatments	Shoot dry weight (g plant^{-1})	Root dry weight (g plant^{-1})
1	0.044 ± 0.01	0.018 ± 0.01
2	0.433 ± 0.09	0.103 ± 0.02
3	0.513 ± 0.09***	0.105 ± 0.03
4	0.564 ± 0.13***	0.107 ± 0.04
5	0.422 ± 0.09***	0.038 ± 0.01***
6	0.580 ± 0.11***	0.104 ± 0.02
7	0.509 ± 0.11***	0.070 ± 0.01**
8	0.465 ± 0.11***	0.042 ± 0.01***

Values represent means (n=12) ± S.E. Significant differences compared to the control: **p<0.01;***p<0.001. (1: distilled water, 2: control, 3: nutrient solution + 5 ml by-product, 4: nutrient solution + 10 ml by-product, 5: nutrient solution+ 50 ml by-product, 6: nutrient solution + 5 ml by-product + 1 ml biofertilizer, 7: nutrient solution+ 10ml by-product + 1 ml biofertilizer, 8: nutrient solution + 50 ml by-product + 1ml biofertilizer)
Source: Own data

Effective organic matter accumulation is impossible without chlorophyll, as an essential component of photosynthetic processes. Based on the research data, the treatments affected the chlorophyll content (Figure 7).

The chlorophyll content of the 2nd and 3rd leaves of maize significantly increased as a result of each treatment. As a result of the treatment 3, the relative chlorophyll content of the second and third leaves increased by 5 Spad units. This value in the treatment 4 was 7 Spad units in the second leaf and 5 Spad units in the third leaf. At the treatment 5, the relative chlorophyll content of the second leaf increased by 5, and that of the third leaf by 6 Spad units. In treatment 6, the growth in the second leaf of corn was smaller - 3 Spad units, in the third leaf 5 Spad units. In treatment 7, the relative chlorophyll content of the third leaf of corn increased by 7.5 Spad units. The chlorophyll content of the sunflower at the treatment 1 was not measured because the leaves did not develop properly. The relative chlorophyll content of the third leaf of sunflower did not change significantly. In the second leaf, the relative chlorophyll content increased by 3 Spad units as a result of the treatments 4, 5, and 6. The treatment 3 increased the relative chlorophyll content by 2 Spad units and the treatment 6 by 2.5 Spad units compared to the control.

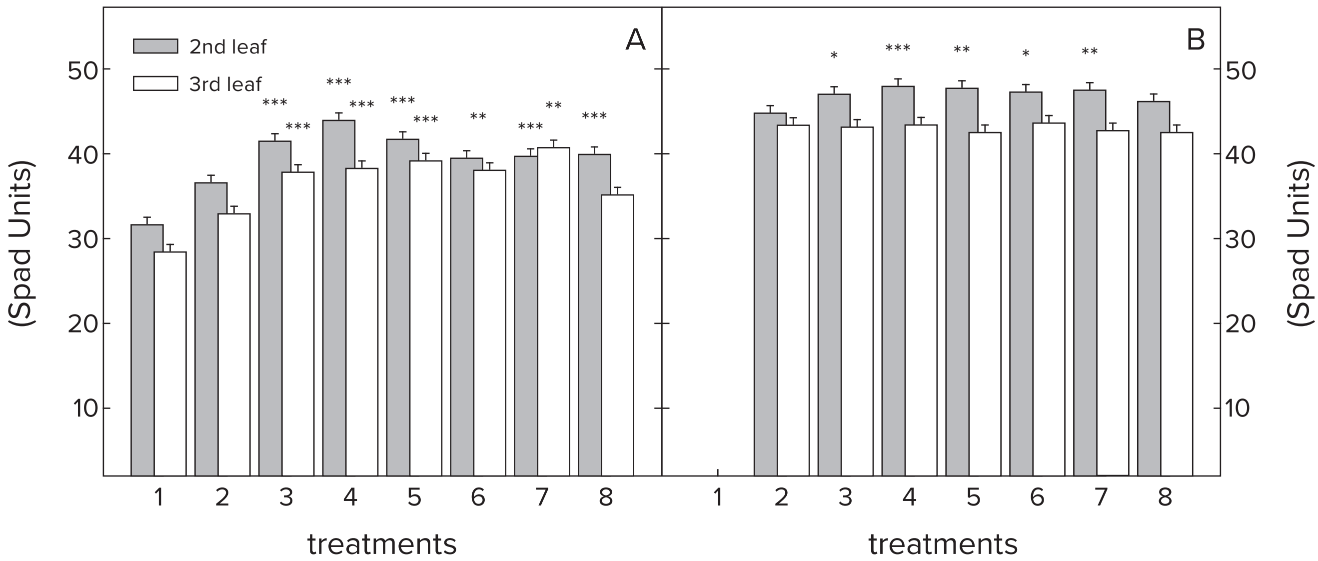

Figure 7: Relative chlorophyll contents of the second and third leaves of maize (A) and sunflower (B) (Spad units) Values represent mean (n = 60) ± S.E. Significant differences compared to the control: **p<0.01;***p<0.001. (1: distilled water, 2: control, 3: nutrient solution + 5 ml by-product, 4: nutrient solution + 10 ml by-product, 5: nutrient solution+ 50 ml by-product, 6: nutrient solution + 5 ml by-product + 1 ml biofertilizer, 7: nutrient solution+ 10ml by-product + 1 ml biofertilizer, 8: nutrient solution + 50 ml by-product + 1 ml biofertilizer)
Source: Own data

Based on the results, the use of biogas by-products for nutrient supply and further investigation can be recommended.

12. Possible Use of Industrial Oily By-products in Agricultural Production

12.1. The Use of Oily Wastes and By-Products in Plant Nutrition

For some industrial societies, disposing of the oily sludge produced during the production and processing of heavy oil is turning into a significant issue. Table 1 displays a few disposal possibilities. Municipalities have historically utilized this sludge to grease roads and reduce dust on rural roads. However, road oiling alone cannot handle the increasing volumes of these contaminants. Landfilling, incineration, and pumping into deep underground are further disposal alternatives. Waste is buried underground during landfilling, where it stays mostly undisturbed and may pollute groundwater. Because of the water and solids in the sludge, as well as environmental issues about airborne particles and ash disposal, incineration is costly.

Land farming of oily sludge is an alternative to landfilling and incineration. Land farming is the application of waste in a dedicated land area and enhancing the biodegradation of the waste by using bioremediation techniques.

This option can provides an economical and environmentally sound approach to oily sludge disposal. Its **limitation** is that objective is often to dispose of the maximum amount of waste in a small area, leading to the accumulation of resistant substances that may prevent the land from being used for agriculture for an extended period. This sludge may be better viewed from an agricultural standpoint as a source of organic carbon, which may transform in time to humus-like materials thereby increasing soil fertility and quality. A one-time application of oily waste as an organic carbon amendment to low organic matter, infertile soils may have the benefit of improving soil productivity.

Petroleum oils affect plant growth in many ways. The oil may immediately kill the plant or delay its growth. It may also depress seed germination and can cause nutrient-deficient conditions due to extensive nutrient immobilization during oil decomposition. Some studies have reported that very low concentrations of hydrocarbons can stimulate the growth of plants.

Oil can affect seed germination in two main ways. At high contamination levels, the oil coats the seed, preventing oxygen and water uptake, which halts germination. Additionally, oil may penetrate the seed and kill the embryo. Even at lower contamination levels, oil can hinder germination.

Numerous studies have shown reduced seed germination after oil or oily waste application. For example, Murphy (1929) reported that even small amounts of oil delayed germination. Isirimah et al. (1989) found that 2% to 4% oil contamination reduced crop emergence by 20% to 50%. However, soil fertilization and bioremediation techniques have been shown to improve seed germination in oil-contaminated soils. Salanitro et al. (1997) observed 50% to 100% inhibition of seed germination in corn, wheat, and oats in untreated oil-contaminated soils. When the soils were fertilized there was no significant difference in seed germination between oil-contaminated soil and the control. There is also variation among plant species in their ability to germinate in the presence of soil. Schwendinger (1968) reported poor germination of sorghum compared to beans and ryegrass in repeatedly oil-contaminated soil. Carr has already published the effect of crude oil on plant growth and root nodule development in 1919. He found a positive effect of 0.75 % crude oil treatments on soybean growth and root development. According to Mackin (1950), crude oil has different (positive and negative) effects on saltgrass and saltwort. The effect depends on the time of application.

Degradation of oil waste is carried out in soil by **microorganisms**. Microorganisms need nutrients for multiplication and growth. The presence of nitrogen, phosphorus, and potassium in addition to smaller levels of zinc, calcium, manganese, iron, sodium, and sulfur is needed for maximum biological growth, and therefore optimum biodegradation. The soil usually contains sufficient quantities of these nutrients except for nitrogen and phosphorus, although this may vary depending on soil type, management, and fertilization history.

The quantity and methods of adding mineral nutrients to oil-contaminated soil can affect the magnitude of biodegradation. Hunt et al. (1973) reported that the addition of ammonium nitrate stimulated biodegradation, but an increase of nitrogen levels above 100 ppm reduced the soil respiration. Using oily wastes and by-products in plant nutrition can present both advantages and limitations, depending on how they are managed and applied.

Oily wastes can contribute organic matter to soil, improving soil structure, and water retention, and promoting beneficial microbial activity. Some oily wastes may contain essential nutrients such as nitrogen, phosphorus, and potassium, albeit in varying concentrations depending on the source and treatment. When properly treated and applied in controlled amounts, oily wastes can enhance soil fertility by providing nutrients and organic carbon necessary for plant growth. Organic matter from oily wastes can improve soil aggregation and aeration, creating a healthier root environment. Oily wastes can be processed through anaerobic digestion to produce biogas, which can be used as a renewable energy source for heating or electricity generation. Utilizing oily wastes in plant nutrition contributes to waste reduction and promotes a circular economy approach by converting waste into valuable resources.

Oily wastes may contain contaminants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other toxic substances. These contaminants can accumulate in soils and pose risks to plant health and human safety if not properly managed and monitored.

Pathogens: Some oily wastes may harbor pathogens that can potentially affect plant health and pose risks to agricultural workers. Improper application or excessive use of oily wastes can lead to nutrient imbalances in soils, potentially causing nutrient leaching, soil acidification, or nutrient toxicity to plants.

Nutrients in oily wastes may not be readily available for plant uptake, requiring proper processing or treatment to enhance nutrient availability. There are often strict regulations governing the use of oily wastes in agriculture and plant nutrition due to environmental and health concerns. Improper management of oily wastes can lead to environmental pollution, including soil and water contamination, affecting ecosystems and biodiversity. Products grown with oily waste-derived nutrients may face consumer resistance or skepticism due to concerns about food safety and environmental impact. Proper treatment and processing of oily wastes are essential to reduce contaminants and pathogens, making them safer for agricultural use. Regular monitoring of soil quality, nutrient levels, and potential contaminants is crucial to ensure that the use of oily wastes does not harm soil health or compromise plant growth. Adherence to local regulations and guidelines regarding the application of oily wastes in agriculture is necessary to mitigate risks and ensure environmental protection.

In conclusion, while there are potential benefits to using oily wastes and by-products in plant nutrition, careful management, treatment, and adherence to regulations are essential to mitigate potential risks and ensure sustainability in agricultural practices.

12.2. Case study: Presentation of an experiment with an oily by-product

The increasing volume of industrial by-products poses environmental and economic challenges, prompting interest in repurposing waste materials for agriculture. This case study presents the findings of an experiment assessing the effects of an oily industrial by-product (OIB) on plant growth. The study aimed to determine its potential as a soil amendment or fertilizer substitute, considering both its benefits and risks. The objective of the experiment was to evaluate the effects of an oily by-product (OIB) on the growth, yield, and health of tomatoes and wheat.

The oily by-product was collected from an oil-refining process, characterized by its high organic matter content and trace elements.

The control soil was a Sandy loam with pH 6.5.

The following treatments were applied:

- T1: Control (no OIB)
- T2: 1% OIB by weight
- T3: 3% OIB by weight
- T4: 5% OIB by weight

Soils were mixed with OIB according to treatment ratios and allowed to stabilize for one week. Seeds of tomato and wheat were sown in pots containing the treated soils.

Plants were grown in a greenhouse with controlled light, temperature, and water supply. The experiment lasted 8 weeks for wheat and 12 weeks for tomato.

Germination rate, plant height, biomass (above-ground and root), yield (fruit production for tomatoes and grain weight for wheat), and soil pH and nutrient content (before and after the experiment) were measured.

The control germination rate was 95% for wheat and 90% for tomato. While at T3, a slight reduction in germination (wheat: 88%, tomato: 85%) was observed. In the case of T4, there was a marked reduction in germination (wheat: 75%, tomato: 70%), possibly due to oil toxicity or altered soil properties.

Based on the experiment data, the control plants showed no visible stress symptoms.

T2 treatment (1% of oily industrial by-product) enhanced growth, and increased the plant height and leaf area. At treatment T3, moderate growth improvement was observed but with occasional signs of stress, such as slight leaf discoloration. While at treatment T4, the highest concentration of oily by-product, stunted growth with yellowing and wilting of leaves occurred, likely due to oil-induced toxicity or anaerobic soil conditions.

Biomass increased by 20% compared to control, indicating positive effects of 1% of oily by-product treatment. Biomass also increased by 10% but the root development was slightly impaired at treatment T3. At the highest concentration of oily by-product treatment, the biomass was reduced by 30% compared to the control, highlighting the detrimental effects of high OIB concentrations.

Examining the effects of oily by-products on yield it was concluded that the 1% treatment caused a yield increase by 15% with larger fruits and better color, while the yield was reduced by 40%, with small and malformed fruits in the case of tomato. The wheat grain weight increased by 12% at T2 and decreased by 35% at T4 treatment.

The oily by-product treatments increased organic carbon and nutrient content but reduced soil aeration at higher concentrations. After harvest, soil treated with T2 retained higher nutrient levels, while T4 showed signs of compaction and reduced microbial activity.

The organic matter and trace nutrients in OIB enriched the soil, promoting plant growth at low concentrations. At 1% concentration, OIB improved soil texture and moisture retention.

High concentrations (5%) inhibited plant growth and yield, likely due to oil's hydrophobic properties creating water and oxygen barriers.

Excessive OIB disrupted soil microbial communities, reducing nutrient cycling.

The presence of industrial contaminants in OIB poses long-term risks for soil and crop safety.

The results suggest that OIB can be beneficial as a soil amendment when applied at low concentrations (around 1% by weight). Beyond this threshold, the negative effects outweigh the benefits, particularly for sensitive crops like tomatoes.

This experiment demonstrates that oily by-products, often considered waste, have potential applications in agriculture when used judiciously. Low concentrations of OIB improved plant growth and yield, while higher concentrations led to toxicity and reduced productivity. Further research is needed to refine application rates, assess long-term soil impacts, and explore strategies for contaminant removal. By integrating OIB into sustainable agricultural practices, industries can reduce waste while enhancing soil health and crop productivity.

13. Metallurgical and Energetic By-Products and Wastes in the Service of Plants

Industrial processes, particularly metallurgical and energy production, generate vast quantities of by-products and waste materials. Historically treated as environmental liabilities, these materials are now recognized for their potential to support sustainable agricultural and ecological practices. By integrating these by-products into plant cultivation, industries, and agricultural sectors can address waste management challenges while improving soil fertility, enhancing plant health, and promoting sustainable development. This chapter shows how metallurgical and energetic by-products and wastes can serve plants, focusing on soil amendments, nutrient supply, and environmental remediation.

Table 14 lists a few wastes and residuals from metallurgical operations.

Table 14: A few leftovers from the refining and smelting of metal (Leonard, 1978)

Metal	Residual
Copper (Cu)	Reverberatory slag Acid plant sludge Dusts Unclassified slurries
Lead (Pb)	Blast furnace slag Slag fines Acid plant sludge Sinter scrubber sludge
Zinc (Zn)	Acid plant sludge Unclassified sludges Retort residues
Aluminum (Al)	Shot blast dust Pot line sludge Cast house dust Pot line skimmings

Metal	Residual
Antimony (Sb)	Blast furnace slag Anolyte sludge
Mercury (Hg)	Kiln or retort residues
Titanium (Ti)	Chlorination sludge
Tin (Sn)	Smelting slag

Source: own editing

Metallurgical and energetic by-products offer significant benefits as **soil amendments**. For instance, slag, a by-product of steel-making, is rich in calcium, magnesium, and silicates. When applied to soils, slag improves soil structure, pH balance, and nutrient availability. Acidic soils, which limit plant growth in many regions, can particularly benefit from slag's liming effect, fostering a favorable environment for root development.

Similarly, fly ash, a by-product of coal combustion, is used to enhance soil aeration and water retention. Its porous structure reduces compaction and supports root proliferation. Additionally, fly ash contains trace elements like potassium and phosphorus, which are essential for plant growth. However, careful regulation is required to mitigate the potential risks associated with heavy metal content in some ash samples.

Industrial by-products often contain **nutrients** that are vital for plant development. For example, phosphogypsum, a waste product from phosphate fertilizer manufacturing, is a valuable source of calcium and sulfur. These nutrients contribute to cell wall formation, enzyme activity, and chlorophyll synthesis, directly impacting plant health and productivity.

Another example is biochar, a carbon-rich by-product of biomass pyrolysis. Biochar enhances nutrient retention in soils, reducing nutrient leaching and making fertilizers more efficient. Its high cation exchange capacity enables plants to access essential nutrients, promoting vigorous growth and higher yields.

Moreover, wood ash, derived from biomass energy production, is a **natural fertilizer** rich in potassium and trace elements like manganese and zinc. When applied judiciously, wood ash can supplement nutrient-deficient soils, enhancing plant vitality.

Metallurgical and energetic by-products play a crucial role in phytoremediation efforts, where plants are used to clean contaminated soils. Red mud, a residue from aluminum production, can be applied to soils polluted with heavy metals to immobilize contaminants, reducing their bioavailability and toxicity to plants. In this way, red mud creates safer conditions for vegetation growth and ecological restoration.

Additionally, sludge from wastewater treatment plants, often considered a waste product, can be processed into biosolids that enrich degraded soils. Biosolids provide organic matter and nutrients to support plant growth while reducing erosion and improving soil microbial activity.

Using energetic by-products like biochar and coal fly ash in agriculture contributes to carbon sequestration. Biochar, when incorporated into the soil, locks carbon in a stable form for decades or even centuries. This not only improves soil quality but also mitigates climate change by reducing atmospheric carbon dioxide levels.

Furthermore, utilizing these by-products **reduces the need for synthetic fertilizers and lime**, whose production processes are energy-intensive and generate significant greenhouse gas emissions. By substituting industrial wastes for conventional inputs, agricultural practices become more sustainable and environmentally friendly.

Despite their potential, the application of metallurgical and energetic by-products in plant cultivation requires careful management. Certain materials may contain toxic elements, such as arsenic, lead, or cadmium, which pose risks to plants, soil health, and human consumers of agricultural products. Strict quality control and regulatory frameworks are essential to ensure these materials are safe for agricultural use.

Another challenge is public perception. Farmers and consumers may be hesitant to adopt practices involving industrial by-products due to concerns about safety and efficacy. Education and transparent research are necessary to build confidence in these sustainable solutions.

Metallurgical and energetic by-products and wastes hold immense potential to benefit plant cultivation while addressing environmental and waste management challenges. Through soil amendments, nutrient supply, and environmental remediation, these materials can transform industrial waste into valuable resources for agriculture. While challenges related to safety and public acceptance remain, ongoing research, stringent regulation, and stakeholder collaboration can pave the way for broader adoption. Harnessing the power of these by-products represents a significant step toward sustainable agriculture and a circular economy, where waste becomes a cornerstone of growth and resilience.

Metallurgical and energetic by-products and wastes can be utilized in various ways to benefit plants and agriculture. These materials often contain valuable nutrients, minerals, and organic matter that can enhance soil fertility and support plant growth.

Metallurgical processes generate various **by-products** that can be beneficial for plant nutrition and soil improvement:

- **Steel Slag**: Steel slag contains calcium, magnesium, iron, and other trace elements that are beneficial for plant growth. It can improve soil pH and structure, enhance water retention, and provide slow-release nutrients to plants. Used in road construction, soil stabilization, and as a substrate in greenhouse agriculture.
- **Phosphorus-rich By-Products**: By-products from phosphorus extraction processes can be recycled as phosphorus fertilizers, crucial for plant growth and development.

Energetic by-products are derived from energy production processes such as biomass combustion, biogas production, and biofuel production.

- **Biochar**: Biochar is produced from biomass pyrolysis and can improve soil fertility, water retention, and microbial activity. It has a high surface area that can retain nutrients and reduce nutrient leaching in soils. Used as a soil amendment, especially in organic farming, to improve soil health and crop productivity.

- **Ash from Biomass Combustion**: Ashes from biomass combustion contain potassium, calcium, phosphorus, and micronutrients beneficial for plants. Can be used to neutralize acidic soils and improve soil pH. Applied as a fertilizer or soil amendment to enhance nutrient availability and soil structure.

Some metallurgical and energetic by-products may contain heavy metals, toxins, or pollutants that can pose risks to soil health and plant growth. Proper testing and treatment are essential before application in agriculture. Adherence to environmental regulations and guidelines is crucial to ensure the safe and sustainable use of by-products in agriculture. Careful consideration of application rates is necessary to prevent overloading soils with nutrients or contaminants. Consumer acceptance and trust in products grown using by-products may influence market demand and acceptance. Advances in technology can enhance the processing and treatment of by-products, making them safer and more effective for agricultural use. Conducting field trials and research studies to evaluate the agronomic benefits and potential risks of using by-products in different agricultural systems. Collaboration between industries, research institutions, and agricultural communities can foster innovation and sustainable practices in utilizing by-products for plant nutrition.

In conclusion, metallurgical and energetic by-products have the potential to contribute to sustainable agriculture by providing valuable nutrients, improving soil fertility, and reducing waste. However, careful management, adherence to regulations, and continuous research are essential to maximize their benefits while minimizing potential risks to soil, water, and environmental health.

13.1. Wood ash

Wood ash, a byproduct of burning wood, has long been recognized as a natural resource with applications in agriculture and horticulture. Traditionally, it has been used as a soil amendment to enhance fertility, providing essential nutrients that promote plant growth. In this essay, we will delve into the composition of wood ash, its benefits and limitations as a plant nutrient, methods of application, environmental considerations, and its role in sustainable agriculture.

Wood ash is primarily composed of the inorganic minerals left behind after combustion. Its chemical composition varies depending on the type of wood burned, combustion temperature, and other factors.

Typically, wood ash is rich in potassium and calcium, making it particularly beneficial for soils that are acidic or deficient in these nutrients. However, it lacks nitrogen, a critical macronutrient for plant growth, necessitating supplementation from other sources.

One of the primary uses of wood ash is to neutralize acidic soils. The calcium carbonate in wood ash acts as a natural liming agent, increasing soil pH and creating a more hospitable environment for nutrient uptake by plants. This is particularly useful in regions with naturally acidic soils, such as parts of the southeastern United States and northern Europe.

Wood ash is an excellent source of potassium, often referred to as "potash" in agricultural contexts. This nutrient is vital for photosynthesis, water movement within plants, and disease resistance. Phosphorus, another key nutrient in wood ash, supports root development and flower and fruit production. Magnesium and other micronutrients also contribute to the overall health and vigor of plants.

As a byproduct of wood-burning stoves, fireplaces, and industrial processes, wood ash is readily available at little to no cost. Its use in agriculture recycles waste material, reducing the need for chemical fertilizers and minimizing environmental impact.

While wood ash offers many benefits, it is not a universal solution.

Excessive use of wood ash can lead to overliming, where the soil becomes too alkaline. This can hinder the availability of certain nutrients, such as iron and manganese, and may lead to nutrient imbalances detrimental to plant health. Wood ash contains soluble salts, which, in high concentrations, can damage plant roots and impair seed germination. This is especially concerning in soils with poor drainage or arid regions.

The nutrient content of wood ash can vary significantly depending on the type of wood burned. Hardwoods, for example, typically produce ash with higher nutrient concentrations than softwoods. This variability makes it challenging to predict its exact impact on soil fertility.

Depending on the source of the wood, ash may contain trace amounts of heavy metals like cadmium, lead, and arsenic. These contaminants can accumulate in the soil over time, posing risks to plant health, groundwater quality, and human health.

Before applying wood ash, it is crucial to conduct a soil test to determine pH and nutrient levels. This ensures that wood ash is used appropriately and in the right quantities.

The recommended application rate for wood ash is generally 10–15 pounds per 1,000 square feet of garden space per year. For agricultural use, rates can range from 1 to 2 tons per acre, depending on soil conditions and crop requirements.

Wood ash should be evenly spread and incorporated into the soil to prevent surface runoff and maximize its effectiveness. This can be done using a rake, tiller, or other agricultural equipment. Some plants, such as blueberries, rhododendrons, and azaleas, prefer acidic soils and may not thrive with wood ash application. Care should be taken to avoid using ash around these species.

The use of wood ash must balance agricultural **benefits** with environmental sustainability.

- Utilizing wood ash as a fertilizer reduces the need for synthetic fertilizers, which require significant energy to produce. This contributes to a lower carbon footprint and aligns with sustainable agricultural practices.
- By repurposing wood ash, communities can reduce waste sent to landfills, promoting a circular economy and reducing the environmental impact of wood-burning activities.
- In the context of sustainable agriculture, wood ash plays a valuable role as part of an integrated nutrient management strategy. Its use supports the principles of reducing waste, recycling nutrients, and minimizing reliance on chemical inputs. Moreover, combining wood ash with other

organic amendments, such as compost or manure, can create a balanced and nutrient-rich soil environment.

- In developing regions, where access to commercial fertilizers is limited, wood ash can serve as an affordable and locally available alternative. It offers a practical solution to improving soil fertility and increasing agricultural productivity, contributing to food security and poverty alleviation.

Research into the use of wood ash as a plant nutrient continues to expand, with a focus on optimizing its application and addressing potential risks. Emerging technologies, such as precision agriculture, can help farmers apply wood ash more effectively, tailoring its use to specific crop and soil needs. Furthermore, advances in ash processing and treatment may allow for the removal of heavy metals, making wood ash a safer and more versatile soil amendment. As interest in organic and sustainable farming grows, wood ash is likely to play an increasingly important role in the global agricultural landscape.

Although it has many benefits, ash particles are lightweight and can be easily carried away by wind or water. This can lead to pollution of nearby water bodies, causing algal blooms and harm to aquatic ecosystems. Proper storage and application methods are essential to mitigate this risk.

13.2. Flue Gas Powder

The agricultural sector is under increasing pressure to meet global food demands while addressing environmental challenges such as soil degradation, nutrient depletion, and pollution. One promising approach to achieving sustainability in agriculture is the repurposing of industrial by-products. Among these, flue-gas powder, a by-product of industrial combustion processes, has gained attention for its potential use as a soil conditioner and plant nutrient. Rich in essential minerals and with properties that can enhance soil health, flue-gas powder offers an innovative solution to managing waste and improving agricultural productivity.

Flue-gas powder, commonly referred to as **fly ash**, is a fine particulate material generated during the combustion of coal or other fuels in industrial facilities, particularly in power plants. The material is collected from the flue gases using electrostatic precipitators or bag filters. Captured by flue-gas cleaning systems, this powder is often composed of:

- Silica (SiO_2): Enhances soil structure and aids in water retention. It also improves plant resistance to pests and diseases.
- Calcium (Ca): Critical for pH adjustment and plant cell wall development, as well as for root and shoot development.
- Potassium (K): Supports flowering and fruiting processes as well as overall plant vigor.
- Iron (Fe), Magnesium (Mg), and Sulfur (S): Micronutrients critical for various physiological processes in plants.

- Trace Elements: Manganese (Mn), zinc (Zn), and copper (Cu) are present in small amounts and contribute to plant metabolism.
- The presence of heavy metals such as arsenic (As), lead (Pb), and cadmium (Cd) in fly ash is a concern, as these can accumulate in the soil and pose risks to plant health and human consumption.

Fly ash is categorized into two main **types** based on its chemical composition:
- Class F Fly Ash: Derived from the combustion of anthracite or bituminous coal, it has a low calcium content (<10%) and is rich in silicate and alumina.
- Class C Fly Ash: Produced from sub-bituminous coal or lignite, it contains higher calcium content (>20%) and exhibits cementitious properties (it can bind other materials and harden over time when mixed with water).

The high surface area and porosity of fly ash make it a suitable candidate for improving soil physical properties, while its chemical composition provides nutrients beneficial for plant growth.

Fly ash offers several **benefits** for agricultural applications. These benefits can be grouped into soil improvement, nutrient supply, and environmental sustainability.

Fly ash enhances the physical properties of soil. The fine particles of fly ash improve soil aeration (due to its porous structure) and water retention, particularly in sandy or degraded soils. Fly ash can neutralize acidic soils due to its alkaline nature, making it suitable for crops requiring neutral to slightly alkaline conditions. The addition of fly ash reduces soil bulk density, improving root penetration and water infiltration.

The nutrient content of fly ash serves as a supplementary source of essential macro and micronutrients for plants. The gradual release of these nutrients ensures long-term soil fertility and minimizes the need for synthetic fertilizers.

Using fly ash in agriculture reduces the burden on landfills and minimizes environmental pollution. The use of fly ash in soils can promote carbon sequestration, contributing to climate change mitigation. The nutrient supply from fly ash reduces reliance on chemical fertilizers, lowering the risk of water pollution from fertilizer runoff.

Fly ash can be applied in various ways to **support plant production**. Its versatility allows for its use in soil amendment, composting, and as a substrate for hydroponics.

Fly ash can be directly mixed with soil to improve its properties. Studies have shown that adding fly ash at rates of 10–30% by weight improves crop yields without adverse effects. It is particularly beneficial for:

Fly ash restores soil fertility in areas affected by mining, industrial activities, or erosion.

Improving Saline and Alkaline Soils: Its neutralizing effect helps reclaim such soils for agricultural use.

When mixed with organic waste, fly ash enhances the composting process by maintaining optimal pH levels and providing additional nutrients. The resulting compost has a balanced nutrient profile, making it an excellent organic fertilizer. Fly ash can serve as a cost-effective alternative to traditional hydroponic substrates like perlite or vermiculite.

Despite its benefits, the use of fly ash in agriculture is not without **challenges**. Addressing these concerns is essential to ensure its safe and effective application.

The presence of toxic heavy metals in fly ash raises concerns about their potential accumulation in soil and crops. Long-term exposure to these metals can have adverse effects on plant health and pose risks to human and animal health throughout the food chain.

The chemical composition of fly ash varies significantly depending on the source and type of coal used. This variability makes it difficult to standardize its application rates and ensure consistent results. The effectiveness of fly ash as a soil amendment depends on soil type, crop species, and local environmental conditions. It may not be suitable for all agricultural systems, requiring careful evaluation before use.

The perception of fly ash as industrial waste can hinder its acceptance in agriculture.

India, one of the largest producers of fly ash, has successfully utilized it in agriculture. Initiatives by the Indian government encourage the use of fly ash in soil reclamation and crop production. Studies have shown significant yield improvements in crops such as wheat, rice, and sugarcane with fly ash application.

China has explored fly ash as a soil amendment in its agricultural sector, particularly in improving saline-alkaline soils in northern regions. Positive results have been reported in terms of soil fertility enhancement and crop yield.

In the United States, fly ash is used in limited agricultural applications, primarily in soil stabilization and erosion control. Ongoing research focuses on addressing environmental concerns to expand its use.

The potential of fly ash in agriculture is immense, but its widespread adoption requires a multidisciplinary approach involving policymakers, researchers, and farmers. Future efforts should focus on establishing guidelines for fly ash composition, application rates, and safety measures. Educating farmers and stakeholders about the benefits and safe use of fly ash. Integrating fly ash into organic and regenerative farming systems to maximize its environmental benefits.

Fly ash, once considered a mere industrial waste, has emerged as a valuable resource for agricultural plant production. Its ability to improve soil properties, provide essential nutrients, and promote environmental sustainability makes it a promising tool for modern agriculture. However, addressing challenges such as heavy metal contamination and variability in composition is crucial for its safe and effective use. With continued research and innovation, fly ash has the potential to contribute significantly to sustainable farming practices, ensuring food security while minimizing environmental impact.

13.3. Soot

The challenge of ensuring global food security while preserving environmental integrity is one of the most pressing concerns of the 21st century. Agriculture is heavily reliant on soil fertility, which is increasingly threatened by overexploitation, nutrient depletion, and pollution. Concurrently, industrial processes and combustion activities generate by-products like soot, which often become environmental pollutants. Soot, primarily composed of carbon particles, trace minerals, and hydrocarbons, has long been regarded as a waste material. However, recent research indicates its potential as a soil amendment and nutrient source. This section explores the feasibility of using soot as a plant nutrient, examining its composition, benefits, challenges, and strategies for safe and effective application in agriculture. Soot, also known as black carbon, is a by-product of incomplete combustion of organic materials such as fossil fuels, wood, and biomass. Its **composition and properties** depend on the source of combustion and the conditions under which it forms.

Soot is rich in elemental carbon, which can contribute to soil organic carbon when properly incorporated into soil. Depending on its source, soot may contain trace minerals like potassium, calcium, magnesium, iron, and phosphorus, which are essential for plant growth. Soot may also contain polycyclic aromatic hydrocarbons (PAHsa) and other organic compounds, some of which are toxic and need careful handling. Soot particles have a high surface area due to their microporous structure, making them capable of adsorbing nutrients and water.

These characteristics position soot as a material with potential agricultural applications, provided its contaminants are managed. Carbon in soot can contribute to the organic carbon pool of soil, improving its structure, aeration, and water-holding capacity. This enhancement supports root development and microbial activity.

Soot contains mineral nutrients that are essential for plant growth. For instance: potassium promotes flowering and fruiting, calcium enhances cell wall integrity, and magnesium is vital for chlorophyll production.

The porous structure of soot helps in aggregating soil particles, enhancing porosity and reducing compaction. This results in improved water infiltration and root penetration.

Soot can adsorb nutrients and water due to its high surface area, reducing leaching and making nutrients more available to plants over time.

Utilizing soot as a soil amendment provides an environmentally responsible way to manage an otherwise harmful by-product. This practice reduces air pollution, mitigates the health hazards associated with soot, and aligns with waste recycling principles.

Incorporating soot into soil can sequester carbon, reducing atmospheric carbon dioxide levels and contributing to climate change mitigation. Compared to commercial fertilizers, soot is a low-cost alternative, especially for resource-poor farmers. Industries generating soot can also reduce disposal costs. By improving soil health and nutrient availability, soot has the potential to boost crop yields and ensure sustainable food production.

For soot to be used effectively and safely in agriculture, certain practices and precautions must be followed:

- The chemical composition of soot varies depending on its source. Before application, soot should be analyzed to determine its nutrient content and contaminant levels.
- Raw soot may contain toxic compounds like heavy metals and PAHs. Pre-treatment processes such as washing, thermal treatment, or chemical stabilization can detoxify soot, rendering it safe for agricultural use.
- Soil testing is crucial to identify pH levels, organic carbon content, and nutrient deficiencies. Soot application should be tailored to the specific needs of the soil.
- Soot should be evenly mixed with soil to prevent uneven distribution of nutrients and carbon. Mechanical tilling can ensure uniform incorporation.
- Blending soot with compost or manure can enhance its effectiveness by balancing its nutrient profile and promoting microbial activity.
- Continuous monitoring of soil and crop performance is essential to adjust soot application rates and prevent potential toxicity.

Despite its potential, the use of soot in agriculture is not without **challenges**:

- Soot may contain heavy metals (e.g., lead, cadmium) and PAHs, which can accumulate in soil and enter the food chain.
- Rigorous pre-treatment processes and compliance with regulatory standards are essential to remove or neutralize contaminants.
- The composition of soot varies widely, making it difficult to standardize its use as a soil amendment.
- Develop classification systems and application guidelines based on soot source and composition.
- Farmers and consumers may have reservations about using soot due to safety concerns. Awareness campaigns, field demonstrations, and transparency in safety protocols can build trust and acceptance. The use of industrial by-products like soot in agriculture may face regulatory hurdles due to concerns about environmental and health impacts. Policymakers should develop clear, science-based regulations to facilitate the safe use of soot while ensuring environmental and human health.

In regions of India, farmers have experimented with soot from biomass combustion in rice paddies. The results showed improved soil structure, reduced pest incidence, and increased yields. Similar to soot, charcoal dust (a by-product of biomass burning) has been used in African countries to enhance soil fertility. Its porous nature and nutrient content have made it a popular soil amendment. In parts of Europe, soot from industrial boilers has been processed and used to rehabilitate degraded soils, showcasing its potential for large-scale agricultural applications.

To fully realize the potential of soot in agriculture, further research and innovation are required:

Detoxification technologies invest in advanced technologies for the efficient detoxification of soot, ensuring safety and effectiveness. Customized fertilizer blends develop formulations that combine soot with other organic and inorganic materials to create balanced fertilizers tailored to specific crops and soils. Long-Term Impact Studies Conduct comprehensive studies to understand the long-term effects of soot application on soil health, crop productivity, and environmental safety. Policy support governments should establish incentives for industries and farmers to adopt soot recycling practices, promoting sustainable agriculture and waste management. Integration with precision agriculture leverage precision agriculture technologies to optimize the application of soot, minimizing waste and maximizing benefits.

The utilization of soot as a plant nutrient represents a compelling opportunity to address two critical global challenges: sustainable agriculture and environmental pollution. By recycling this often-overlooked by-product, we can enhance soil fertility, reduce reliance on synthetic fertilizers, and mitigate the environmental impacts of industrial waste. While challenges such as contamination risks and public perception remain, these can be addressed through rigorous research, innovative technologies, and supportive policies. Harnessing soot in agriculture is not merely an exercise in waste management; it is a step toward a more resilient, sustainable, and environmentally conscious agricultural future.

13.4. Metallurgy Lime Sludge

Metallurgy lime sludge, a by-product of various industrial processes, offers untapped potential for sustainable agricultural practices. Composed primarily of calcium carbonate ($CaCO_3$) and other mineral elements, lime sludge often ends up in landfills, contributing to waste management challenges. However, when appropriately processed and applied, this by-product can serve as a valuable soil amendment and nutrient source for crops.

Lime sludge is generated during industrial processes such as:

- Steel Manufacturing: Lime is used as a fluxing agent in blast furnaces to remove impurities, resulting in lime-rich residues.
- Sugar Refining: Calcium hydroxide purifies sugar, producing lime sludge as a by-product.
- Water Treatment Plants: Lime is added to neutralize acidity and remove impurities, leading to sludge accumulation.

The primary component of lime sludge is calcium carbonate, which plays a critical role in correcting soil acidity. Other constituents may include magnesium, silicon, and trace amounts of iron, manganese, and zinc. These secondary elements can contribute to plant nutrition when the sludge is applied to agricultural land:

- Calcium carbonate enhances soil aggregation, promoting better water infiltration, aeration, and root penetration. This improvement in soil physical properties reduces erosion and waterlogging risks.
- Calcium is vital for plant cell wall integrity, root development, and enzyme activity. Lime sludge provides a readily available source of calcium, supporting healthy crop growth and resilience against environmental stressors.
- One of the most significant benefits of metallurgy lime sludge is its ability to neutralize acidic soils. Soil acidity, often exacerbated by the prolonged use of chemical fertilizers, reduces the availability of essential nutrients to plants. Applying lime sludge raises soil pH, creating an environment conducive to nutrient uptake.
- Depending on its source, lime sludge may contain magnesium and trace elements like iron and zinc, which are essential for enzymatic functions and photosynthesis in plants.
- Utilizing lime sludge in agriculture diverts it from landfills, mitigating waste accumulation and reducing environmental hazards. This practice aligns with circular economy principles, transforming waste into a valuable resource.
- Compared to commercial lime and fertilizers, metallurgy lime sludge is often a low-cost alternative. This affordability makes it an attractive option for farmers, particularly in resource-constrained regions.
- Lime sludge can complement or replace synthetic fertilizers for certain soil types, lowering the environmental footprint associated with chemical fertilizer production and application.
- By improving soil conditions and nutrient availability, lime sludge contributes to increased agricultural productivity and better-quality crops.

Soil testing is crucial to determine pH levels, nutrient deficiencies, and the appropriate dosage of lime sludge. Over-application poses **challenges** that can lead to soil alkalinity, adversely affecting plant growth.

- Raw lime sludge may contain contaminants such as heavy metals, organic residues, or industrial chemicals. Pre-treatment processes, such as washing, filtration, and thermal treatment, are necessary to ensure its safety and efficacy as a soil amendment.
- Lime sludge should be evenly distributed and incorporated into the soil using plowing or harrowing to ensure uniform pH adjustment and nutrient availability.
- Applying lime sludge during fallow periods or before planting allows sufficient time for pH adjustments. Certain crops, such as legumes, maize, and wheat, respond particularly well to lime applications.
- Industrial lime sludge may contain heavy metals such as cadmium, lead, and arsenic, which can accumulate in soil and crops, posing risks to human and animal health.
- Implement stringent quality control measures and pre-treatment processes to remove or immobilize contaminants before application.

- The transportation and application of lime sludge can be costly and labor-intensive, particularly for small-scale farmers.
- Establish local processing units and distribution networks to reduce transportation costs. Government subsidies or industry partnerships can further alleviate economic burdens.
- Farmers and consumers may harbor concerns about using industrial by-products in agriculture due to safety and effectiveness doubts. Regulatory approvals may also be time-consuming and complex. Conduct awareness campaigns, pilot studies, and field demonstrations to showcase the benefits and safety of lime sludge applications. Governments should streamline regulatory processes and offer incentives for its adoption.
- The nutrient composition of lime sludge varies depending on its industrial source, leading to inconsistent results in agricultural applications. Standardize processing methods and develop guidelines for dosage and application based on source-specific analyses.

In India, lime sludge from sugar refineries has been successfully used to improve the productivity of acidic soils in sugarcane-growing regions. Farmers reported enhanced soil fertility and reduced input costs. Lime sludge derived from steel slag has been used in Brazil to rehabilitate acidic pasture lands, supporting livestock farming and increasing forage yields.

In European countries, lime residues from water treatment plants have been repurposed for agricultural use, contributing to soil stabilization and nutrient enrichment. To fully harness the potential of metallurgy lime sludge as plant nutrition, several research and policy initiatives are necessary:

- Invest in advanced processing methods to detoxify lime sludge and optimize its nutrient content.
- Blend lime sludge with other organic or inorganic materials to create tailored fertilizers suited to specific crops and soil types.
- Governments should promote the use of lime sludge through subsidies, tax benefits, and environmental regulations that encourage industrial waste recycling.
- Encourage partnerships between industries, research institutions, and agricultural organizations to explore innovative applications and address safety concerns.

Metallurgy lime sludge, an often-overlooked industrial by-product, holds significant promise as a sustainable source of plant nutrition. By addressing soil acidity, enhancing nutrient availability, and promoting waste recycling, lime sludge can play a pivotal role in advancing sustainable agriculture. However, its successful integration into farming practices requires overcoming challenges related to safety, logistics, and public perception. Through collaborative efforts, innovative technologies, and supportive policies, lime sludge can transition from an environmental burden to a valuable agricultural resource, contributing to a greener and more resilient future.

13.5. Case study: Examination of the effects of wood ash originating from a Hungarian agricultural company

The use of renewable forms of energy is a central issue today. The planting of energy forests and energy lawns is already going on intensively today. The partial transition of the power plants to this new fuel also means that due to the intensive production of firewood and grass, the soils become impoverished in many hard-to-replace (micro and macro) nutrients, and their productivity may decrease significantly within a short time. On the other hand, after burning the new type of energy carrier, a significant amount of by-products, ash, is produced. In simple terms, this means that almost all of the inorganic components of a vegetable fuel extracted from a large area are concentrated in one place, in the vicinity of the power plant, while the area producing the fuel is continuously depleted of these nutrients.

In biomass-based power plants and heating plants, tens of thousands of tons of ash are generated every year, the treatment and disposal of which as waste is costly and also poses an environmental risk.

The goal was to investigate the effect of charcoal and straw ash on the initial growth of corn and sunflower and the related physiological processes in laboratory conditions, to propose a wider, practical use of the resulting by-product. The study investigated the chemical composition of ash from the Törökszentmiklós Mezőgazdasági ZRT farm and its physiological effect on plants.

At the company, the resulting ash is not used to restore soil strength, as it is not possible to examine the composition of the ash, especially the potassium content. The opinion is that if the ash formed from incinerated by-products turns out to be positive from the point of view of soil improvement after appropriate testing, it could be spread to increase the productivity of the soil and this could mean a higher yield and additional competitiveness for the economy. Based on the plant physiology tests of the ash and straw ash by-products used, it could be concludes that the effect of the different treatments was different for the two test plants. Based on the tests, it could be further concluded that the treatments had a different effect on monocotyledonous and dicotyledonous plants. The wood and straw ash produced as an agricultural by-product contains essential elements for plants in significant concentrations. The concentration of the measured elements can be considered close to optimal. Wood and straw ash can be a significant nutrient supplement in the nutrient supply of plants. Its importance is enhanced by the fact that it can be a recycling of a by-product, and that wood and straw ash are not considered classic chemicals, i.e. they are also produced under natural conditions.

The pH of the aqueous solution made from ash is strongly alkaline. Due to the alkalizing effect of the soil, wood ash cannot be used originally on alkaline soils, but its effect can be very favorable on acidic soils, it can only be used with close to neutral soil pH with thorough tests. The possibility of application is ensured by the extremely low solubility of ash. This favorable effect can result in a decrease in the absorption of heavy metals by plants grown on acidic soils, which is also significant from the point of view of human and animal nutrition. Ash can be suitable for restoring the natural state of soils acidified by human activity, so environmental protection aspects also justify further investigations. Wood and straw ash increased the dry matter content of the plants and catalyzed their development, but their addition in the germination experiment on their own worsened the germination rate, so it could be used mainly concerning plant nutrients applied afterward.

13.6. Results of the case study

Sunflower (*Helianthus annuus* L.) was used as test plants. The surface of the seeds was sterilized with 30% hydrogen peroxide. After that, the seeds were rinsed multiple times with distilled water before being immersed in a 10 mmol $CaSO_4$ solution for 4 hours to promote germination. The seeds were germinated at 22 °C between wet filter paper to ensure that the seedlings' polarity was naturally determined. Sunflower seedlings with 4 cm hypocotyls were placed into a nutrition solution.

To grow the plants, a nutrient solution with the following composition was used: 2.0mM $Ca(NO_3)_2$, 0.7mM K_2SO_4, 0.5mM $MgSO_4$, 0.1mM KH_2PO_4, 0.1mM KCl, 10µM H_3BO_3, 1µM $MnSO_4$, 1µM $ZnSO_4$, 0.2 µM $CuSO_4$, 0.01 µM$(NH_4)_6Mo_7O_{24}$, and 10^{-4} M FeEDTA.

Wood ash and straw ash were dissolved in distilled water (1g test materials + 100 ml water), filtered, and added to the nutrient solution.

Phylazonit MC®, a bacterium-based biofertilizer containing *Azotobacter crococcocum* (1–2x10^9 cm^{-3}) and *Bacillus megatherium* (1–2x10^8 cm^{-3}) strains, was applied at a concentration of 1 ml/L.

The environmental conditions were controlled: light intensity 300 µmol $m^{-2}s^{-1}$, temperature 25/20°C (day/night), relative humidity (RH) 65–75%, and a light/dark period of 16/8 hours.

There are many elements, essential and toxic elements as well, in the wood ash and straw ash (Table 15).

Table 15: Contents of the examined elements in the wood ash and straw ash (mg kg^{-1})

Elements	Wood ash	Straw ash
Al	1,857	6,423
B	76	165
Ba	336	145
Ca	28,555	129,424
Cr	10	9
Cu	30	55
Fe	2,495	6,401
K	96,200	109,494
Li	7	14

Elements	Wood ash	Straw ash
Mg	10,698	31,732
Mn	411	408
Na	2,420	14,492
P	15,014	13,157
S	4,428	8,475
Sr	206	762
Ti	136	147
Zn	194	599

Values are mean (n = 3)

Source: Own data

13.6.1. The effect of wood ash and straw ash on germination

Mustard is one of our most sensitive plants, which is why it is commonly used in toxicity tests. The solubility of the wood ash and straw ash of is low, but even when dissolved in small amounts, it significantly increases the pH of soil or the nutrient solution. The pH of wood ash was 12.44 while the pH of straw ash was 10.04. These high pH values can be the reason of the extremely low germination percentage in cases of wood ash. The data of the germination experiment is summarized in Table 16.

Table 16: The effect of wood ash and straw ash on mustard germination.

Days	Treatments				
	control	A	B	C	D
	germination %				
2	88.00 ± 4.58	12.00 ± 2.00***	40.00 ± 10.44**	91.67 ± 3.51	92.67 ± 3.21
3	5.67 ± 5.13	8.33 ± 7.09	34.00 ± 0.00**	3.67 ± 1.15	3.33 ± 0.58
4	1.33 ± 1.25	1.67 ± 1.53	13.00 ± 0.00**	1.00 ± 0.58	1.67 ± 1.15
5	0.67 ± 0.58	0.00 ± 0.00	6.33 ± 0.00**	1.33 ± 0.58	0.33 ± 0.58
6	0.33 ± 0.58	0.33 ± 0.58	1.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Total	95.67	22.00	93.33	97.67	98.00

Values represent means ± S.E (n = 100). Control: distilled water, A: wood ash, B: straw ash C: 0.5 g + 50 ml wood ash, D: 0.5 g + 50 ml straw ash. Significant differences compared to the control: $^{**}p < 0.01$; $^{***}p < 0.001$.

Source: Own data

During the germination test, germination percentage and germination vigor were examined. The increased germination vigor means that most of the seeds germinate quickly at the same time, which makes germination simultaneous. Regarding the total germination percentage, wood ash and straw ash reduced the germination, while the germination percentage increased. The germination percentage on the second day significantly decreased at wood ash and straw ashe compared to the control.

13.6.2. The effect of wood ash and straw ash on dry weight and chlorophyll content

Dicotyledons are especially sensitive to rhizosphere pH; even mildly basic conditions restrict nutrient uptake because high pH neutralizes root proton excretion, hence inhibiting H^+ transport mechanisms like antiport and symport. Inhibition of transport processes deprives the plant of necessary nutrients, causing reduced growing

Table 17. The dry weight of the sunflower shoots and roots (g plant^{-1}) of different treatments.

Treatments	Shoot	Roots
Distilled water	0.031 ± 0.00	0.011 ± 0.00
Control	0.309 ± 0.06	0.064 ± 0.02
Wood ash	0.432 ± 0.09**	0.071 ± 0.03
Straw ash	0.340 ± 0.08	0.068 ± 0.03

Values represent means ± S.E (n = 5). Significant difference compared to the control: **$p < 0.01$. *Source:* Own data

The wood ash and straw ash increased the dry weight of sunflower shoots. The dry weight of sunflower shoots increased by 40% at the ash treatment and by 20% at the straw ash treatment compared to the control. There was no significant difference in the dry weight of the roots compared to the control. Sunflower root dry weight increased with all treatments, but this increase was not significant. At the same time, more intensive root growth is favorable, because the plant can absorb water and nutrients on a larger surface, thereby increasing its stress tolerance. The amount of nutrients required for synthetic processes increases, which results in a larger leaf surface, thus more intensive photosynthesis, and ultimately an increased accumulation of organic matter. In the case of distilled water treatment, a reduced accumulation of dry weight can be observed, since distilled water does not contain nutrients important for plants, so their growth is inhibited, and the plant only refers to its stored nutrient supply. Effective accumulation of organic matter is not possible without chlorophyll, an essential component of photosynthetic processes. The treatments affected dry weight, behind which the changes in photosynthetic activity and chlorophyll content were hypothesized. According to the measurements, the treatments affected the chlorophyll content (Table 18).

Table 18. The relative chlorophyll content (SPAD-Units) in the 2nd and 3rd leaf of sunflower.

Treatments	2nd leaf	3rd leaf
Distilled water	-	-
Control	42.93 ± 1.77	38.65 ± 2.42
Wood ash	43.14 ± 1.97	40.40 ± 1.87
Straw ash	43.85 ± 1.82	39.67 ± 1.98

Values represent means ± S.E (n = 60) *Source:* Own data

There were no significant differences among the wood ash, straw ash, and control.

13.6.3. Influence of Wood Ash and Straw Ash on Nutrient Content in Sunflower Shoots and Roots

The elements found in the shoot and root of a sunflower are shown in Table 19. Most nutrients (B, Ca, K, Mg, P, and S) were detected in higher amounts in the shoot than in the root. Potassium plays an important role in maintaining the osmotic potential, in the photoactive reaction of the stomata, in carbohydrate metabolism, and in membrane transport. It is of great importance in the production and transport of organic matter in plants. On the other hand, the concentration of Cu, Fe, Mn, and Zn was higher in the root. Chromium accumulated in the sunflower roots as a result of the treatments. Due to the higher Cr concentration in the root, it can be assumed that the transport from the root to the shoot was inhibited, so less Cr was transported to the shoot. No toxic changes were visible on the cultivated plants.

Table 19. The concentration of B, Ca, Cu, Cr, Fe, K, Mg, Mn, P, S, and Zn in the shoot and root of sunflower (mg kg^{-1})

Elements	Treatments			
	Distilled water	Control	Wood ash	Straw ash
	Elements content in the shoot of sunflower (mg kg^{-1})			
Al	9.72	6.22	7.88	10.4
B	71.6	57.2	47.8	43.8
Ca	12,246	29,639	40,045	41,411
Cu	0.52	0.34	0.39	0.35
Cr	0.52	0.34	0.39	0.35
Fe	55.9	167	255	343
K	3,700	49,805	39,344	29,531

Elements	Treatments			
	Distilled water	Control	Wood ash	Straw ash
	Elements content in the shoot of sunflower (mg kg^{-1})			
Mg	2,288	3,599	4,039	3,785
Mn	17.9	60.3	80.7	53.3
P	2,087	6,212	7,512	8,922
S	2,580	6,029	6,118	6,044
Zn	125	36.3	37	38.4
Elements	**Treatments**			
	Distilled water	**Control**	**Wood ash**	**Straw ash**
	Elements content in the root of sunflower (mg kg^{-1})			
Al	153	32.5	77.1	29.3
B	28.5	28.8	27	29.9
Ca	4,871	5,872	5,411	6,200
Cu	381	10.5	8.43	7.29
Cr	0.85	0.82	1.12	2.05
Fe	334	565	704	565
K	1,549	23,675	20,446	20,859
Mg	379	1,020	867	970
Mn	9.69	49.7	57.1	23
P	2,330	4,162	3,190	3,958
S	2,861	4,826	4,407	4,078
Zn	481	38.4	32.3	42.9

Values are mean (n = 3) *Source:* Own data

14. Possibilities of Using Industrial By-Products in Forestry

Forestry plays a critical role in the global ecosystem, providing resources like timber, improving air quality, and offering habitats for countless species. As industries grow, they generate significant by-products, many of which remain underutilized or are treated as waste. However, the convergence of industrial innovation and sustainable forestry practices presents opportunities to repurpose these by-products to benefit forestry. This chapter explores the potential uses of industrial by-products in forestry, focusing on soil enhancement, pest control, and the reduction of carbon emissions.

One of the most promising uses of industrial by-products in forestry is soil amendment. Certain by-products, such as fly ash from coal power plants, can improve soil texture, water retention, and nutrient availability. Fly ash contains essential elements like calcium, magnesium, and potassium, which promote tree growth. Additionally, the alkaline properties of fly ash help counteract soil acidity, a common challenge in forest management.

Another example is biochar, a by-product of biomass pyrolysis. **Biochar** enhances soil fertility, boosts microbial activity, and increases carbon sequestration. Research has demonstrated its effectiveness in improving seedling survival rates and tree growth, making it an ideal supplement for degraded or nutrient-poor forest soils.

Industrial by-products can also play a role in pest and disease management. For instance, wood ash, a residue from biomass combustion, has been used as a natural deterrent for pests in forestry. Its high mineral content disrupts pest breeding cycles and reduces the need for chemical pesticides, which can harm non-target species and contaminate water sources.

Similarly, certain by-products from the food and pharmaceutical industries, such as **chitin** derived from shellfish waste, have shown potential as biopesticides. Chitin-based treatments enhance tree resistance to fungal infections and other pathogens, promoting healthier forest ecosystems.

Recently chitin and its derivatives were used for remediation of organic and inorganic contaminants from soil and water. Chitinase can be used in the conversion of chitinous waste into biofertilizer, insecticides, and fungicides so that these can be more potent and ecofriendly as compared to chemically synthesized active agents.

Forestry and industrial sectors are major contributors to global carbon emissions. By integrating industrial by-products into forestry, there is potential to reduce these emissions significantly.

For example, incorporating slag, a by-product of steel manufacturing, into forest soils can act as a carbon sink, capturing and storing atmospheric CO_2.

Moreover, reusing organic by-products, such as pulp and paper industry residues, can create carbon-rich composts that support tree growth while simultaneously reducing the need for synthetic fertilizers. This approach not only sequesters carbon but also minimizes the environmental footprint of industrial waste disposal.

Repurposing industrial by-products for forestry applications can generate economic and environmental benefits. Industries can reduce waste disposal costs by supplying by-products to forestry operations, creating a circular economy. Forestry stakeholders, in turn, benefit from affordable and sustainable resources to improve tree health and productivity. Environmentally, this practice minimizes the volume of industrial waste entering landfills, reduces soil and water pollution, and promotes sustainable forest management. Integrating these practices aligns with global efforts to achieve sustainability goals and combat climate change.

Despite its potential, the use of industrial by-products in forestry faces **challenges**:

- Not all by-products are safe for environmental use; some may contain heavy metals or toxic compounds that could harm forest ecosystems. Thorough testing and regulation are essential to ensure the safety of these materials.
- Another challenge is the lack of awareness and infrastructure for transporting and applying by-products to forests. Collaboration between industries, governments, and forestry experts is necessary to overcome these barriers and scale up the implementation of such practices.

The use of industrial by-products in forestry offers immense possibilities for enhancing sustainability, improving forest health, and addressing environmental challenges. By focusing on soil enhancement, pest management, and carbon sequestration, industries and forestry sectors can work together to create a more sustainable future. While challenges remain, ongoing research and collaboration can unlock the full potential of industrial by-products, transforming waste into a valuable resource for forestry.

Using industrial by-products in forestry can offer several environmental and economic benefits, provided that these materials are used responsibly and safely.

14.1. Wood Chips and Sawdust

Sawmills and woodworking industries generate **wood chips** and **sawdust** as by-products. These materials can be used in forestry for mulching around trees, erosion control on slopes, or as biomass for energy production (e.g., bioenergy plants).

Wood chips and sawdust are versatile materials that can be beneficially used in plant production, especially in horticulture and agriculture. Here are several ways wood chips and sawdust can be utilized:

- Mulching with wood chips and sawdust provides several benefits for plant health and soil management. Wood chips and sawdust help retain soil moisture by reducing evaporation from the soil surface, thus reducing the frequency of irrigation needed. A thick layer of wood chips or sawdust can suppress weed growth by blocking sunlight and inhibiting weed seed germination. Mulch moderates soil temperature fluctuations, keeping roots cooler in summer and warmer in winter, which can benefit plant growth.
- On slopes and bare soil, wood chips and sawdust can help prevent erosion by reducing water runoff and holding soil particles in place.
- Incorporating wood chips and sawdust into soil can improve its structure, fertility, and nutrient availability. As wood chips and sawdust decompose, they contribute organic matter to the soil, enhancing its nutrient-holding capacity and promoting beneficial microbial activity. Sawdust and wood chips decompose slowly, releasing nutrients such as nitrogen, phosphorus, and potassium over time, which can benefit plant growth. In clay soils, sawdust helps improve aeration and drainage, while in sandy soils, it increases water retention and nutrient availability.
- In addition, sawdust and wood chips can be used as carbon-rich materials in composting processes. In compost piles, sawdust and wood chips balance the carbon-to-nitrogen ratio when mixed with nitrogen-rich materials like kitchen scraps or grass clippings. The insulating properties of wood chips and sawdust help maintain compost pile temperatures, promoting efficient decomposition of organic matter. Composted wood chips and sawdust produce a nutrient-rich compost that can be used as a soil amendment to enhance plant growth.

Sawdust decomposes faster than wood chips due to its finer texture. This can affect how long-lasting their effects are in soil or as mulch. Fresh sawdust and wood chips can temporarily tie up soil nitrogen as microorganisms decompose the material. To mitigate this, nitrogen fertilizer may need to be added initially, or aged (weathered) wood chips and sawdust may be used. It is important to ensure that the wood chips and sawdust used are free from contaminants such as chemicals or treated wood, to prevent harm to plants or the environment.

When applying mulch, a 2–4 inch layer of wood chips or sawdust should be spread around plants, keeping a gap around the stems to avoid rot and pest problems. If incorporating into soil, the wood chips or sawdust should be thoroughly mixed to ensure even distribution and prevent clumping.

Wood chips and sawdust are suitable for a wide range of plants, including ornamentals, vegetables, and fruit trees, but may not be ideal for plants preferring acidic conditions unless they are aged or composted first.

In summary, wood chips and sawdust are valuable resources in plant production, providing benefits such as moisture retention, weed suppression, soil improvement, and nutrient release. Proper application and consideration of their properties are essential to maximize their effectiveness and ensure sustainable plant growth.

14.2. Paper and Pulp Industry By-Products

Sludge generated from paper mills, often containing cellulose fibers and inorganic materials, which can be beneficially reused in forestry. It can be applied to forest soils to improve organic matter content, nutrient availability, and soil structure.

The paper and pulp industry generates several by-products that can be effectively utilized in plant production, offering both economic and environmental benefits. Here are some key by-products and how they can be used:

Paper sludge is a by-product of the paper recycling and manufacturing process. It typically contains cellulose fibers, clay fillers, and other materials used in paper production.

Paper sludge can be applied to agricultural land or gardens as a soil amendment. It improves soil structure, increases water retention, and enhances nutrient availability due to its organic content. The organic matter in paper sludge contributes to soil fertility and stimulates microbial activity, which benefits plant growth. Paper sludge contains nutrients such as nitrogen, phosphorus, and potassium, which are slowly released as it decomposes, providing a sustainable nutrient source for plants. Incorporating paper sludge into compost piles helps balance carbon-to-nitrogen ratios and produces nutrient-rich compost that can be used to enrich soils.

14.3. Fiber Residues

Residual fibers from paper and pulp production can be used in products like cellulose insulation or as additives in soil amendments. Fiber residues are leftover materials from the paper and pulp production process, including fibers that are too short or damaged for further use.

Fiber residues can be used as a soil conditioner to improve soil structure, water retention, and aeration. They help create a healthy root environment for plants. Like other organic materials, fiber residues can be used as mulch around plants. They help suppress weeds, conserve soil moisture, and regulate soil temperature.

Using paper and pulp industry by-products, such as paper sludge and fiber residues in plant production, reduces waste and maximize the use of materials that would otherwise be discarded. These by-products contribute organic matter to soils, enhancing fertility, improving soil structure, and supporting beneficial microbial activity.

Paper sludge and fiber residues contain valuable nutrients that can be recycled back into agricultural systems, reducing the need for synthetic fertilizers. Utilizing by-products as soil amendments or mulch can reduce production costs for growers and gardeners. Ensuring that paper sludge and fiber residues used in plant production are free from contaminants and meet regulatory standards for heavy metals and other pollutants is critical. Following the guidelines for application rates avoids overloading soils with nutrients or organic matter, which could potentially harm plants or impact soil quality. Awareness of local regulations and guidelines regarding the use of industrial by-products in agriculture ensures compliance with environmental and health standards.

Incorporating paper and pulp industry by-products into plant production systems offers sustainable solutions for soil improvement, nutrient recycling, and waste reduction. With proper management and consideration of quality and regulatory requirements, these by-products can contribute significantly to enhancing soil health and supporting healthy plant growth in agricultural and horticultural settings.

14.4. Agricultural By-Products

Agricultural residues such as straws or husks can be used as mulch or soil amendments in reforestation projects, promoting soil health and reducing erosion. Utilizing by-products reduces waste and maximizes the use of materials that would otherwise be disposed of in landfills or incinerators. By-products are often available at lower costs compared to virgin materials, providing economic benefits to forestry operations. Recycling and reusing by-products can reduce the environmental footprint of forestry activities by conserving natural resources and reducing greenhouse gas emissions associated with waste disposal.

Industrial by-products must be tested for contaminants to prevent harm to soils, water quality, and forest ecosystems, while adhering to environmental regulations for their safe use in forestry.

Proper application methods must be followed to maximize the benefits and minimize potential risks of using industrial by-products in forestry.

Incorporating industrial by-products into forestry practices can contribute to sustainable forest management by enhancing soil fertility, conserving resources, and reducing waste. However, careful consideration of quality, contaminants, and regulatory requirements is crucial to ensure that these materials are used effectively and safely without harming forest ecosystems.

Using **wood ash** in forestry can be beneficial if applied correctly, as it contains valuable nutrients that can enhance soil fertility and promote tree growth. Wood ash is primarily composed of calcium carbonate (which neutralizes soil acidity) and contains varying amounts of essential plant nutrients such as:

Potassium (K): Important for overall tree health, including growth, root development, and disease resistance.

Calcium (Ca): Essential for cell wall structure and overall tree vigor.

Magnesium (Mg): Necessary for chlorophyll production and photosynthesis. Depending on the wood type and burning conditions, wood ash may also contain trace amounts of micronutrients like zinc, copper, and manganese.

The scientists conducted a research is part of a network called AshNet, which is exploring wood ash application to improve forest soils in field trials across a range of Canadian forest ecosystems.

The objective of this experiment was to quantify the impact of wood ash on forest growth and comprehend how it affects the physical, chemical, and biological characteristics of soil. Forests that have lost nutrients due to harvesting may benefit greatly from ash. Tree stems, or main trunks, are cut down for wood products during traditional forest harvesting. The nutrients within them are eliminated along with the stems. Treetops, branches, and smaller trees that can be used as biomass energy sources are removed during more intensive forest harvesting. On the one hand, using biomass energy can cut down on the consumption of fossil fuels. However, the forest loses considerably more nutrients when biomass is harvested intensively. The fertility of forest soil may decline as a result of this increased nitrogen loss.

Scientists also investigated how ash affects microscopic microbes as well as insects and spiders. Wood ash's high pH can make it highly caustic, therefore it's crucial to make sure it doesn't harm soil organisms. These communities and the general health of the soil may occasionally be enhanced by the addition of alkaline-rich wood ash to extremely acidic forest soil.

Wood ash has alkaline properties due to its calcium carbonate content. It can be used to neutralize acidic soils, creating more favorable conditions for tree growth, especially in areas with naturally acidic soils. Wood ash releases nutrients slowly over time as it breaks down in the soil. This gradual release provides a sustainable source of potassium and other essential nutrients for tree uptake. When applied in moderation, wood ash can improve soil structure by increasing aggregation and enhancing water infiltration. Wood ash can stimulate microbial activity in the soil, which aids in nutrient cycling and overall soil health. The following facts need to be considered:

It is essential to apply wood ash sparingly. Excessive application can raise soil pH too high, potentially inhibiting nutrient availability and affecting tree health. A general guideline is to apply no more than 20 pounds of wood ash per 1000 square feet of soil. It is recommended to apply wood ash during periods of low wind to minimize dust and ensure even distribution over the soil surface. Also, it is important to mix wood ash thoroughly into the topsoil to prevent runoff and ensure nutrients are available to tree roots. Moreover, regular monitoring of soil pH and nutrient levels is necessary for adjusting future applications of wood ash accordingly. It is further recommended to use wood ash from clean, untreated wood sources, and to avoid ash from painted, stained, or pressure-treated wood, as it may contain harmful chemicals that can impact soil and tree health. Avoiding application of wood ash near water bodies or in sensitive ecosystems can affect water quality due to its alkalinity and nutrient content. Awareness of local regulations regarding the use of wood ash in forestry and ensuring compliance with guidelines for soil amendments is important.

When used responsibly and in moderation, wood ash can be a valuable resource for enhancing soil fertility and promoting tree growth in forestry. It provides essential nutrients, helps adjust soil pH, and contributes to overall soil health when applied following recommended guidelines and considering environmental considerations.

Summary

Sustainable development faces significant global and national challenges. Rapid population growth is straining limited agricultural land, while efforts to increase food production through farming intensification and chemical use are driving up CO_2 emissions and causing environmental harm. In Hungary, however, favorable agricultural conditions ensure sufficient food production.

Globally, increasing industrial activity produces large volumes of by-products, created through energy-intensive processes that contribute to environmental issues. These by-products, often rich in nutrients, offer a sustainable alternative to expensive chemical fertilizers and can help lower CO_2 emissions. To ensure their safe use, they must be non-toxic to plants and environmentally sustainable.

Protecting the environment is one of the most crucial tasks today. The Earth is suffering and cannot withstand the growing environmental strain without consequences. It has become clear that no issue is isolated, everything is interconnected. This is especially true for the environmental changes. While the deforestation of the Brazilian rainforests may seem like an issue for just one country, the economic growth in both developed and rapidly developing nations leads to high production levels and increased pollution. These emissions affect everyone globally.

Increased CO_2 and SO_2 emissions have well-known effects, including global warming and acid rain, which can kill vegetation. Soil acidification isn't just from acid rain; it also results from deforestation, which removes nutrients stored in trees but originally came from the soil. This lowers soil pH and buffering capacity, leading to higher heavy metal uptake. While aluminum (Al) isn't technically a heavy metal, it has similar harmful effects, damaging plant cells and disrupting metabolism, eventually causing plant death. Many scientists link increased Al uptake to the death of European forests. Other heavy metals also rise as soil pH drops. In Hungary, the population consumes a large amount of fresh produce, much of it from poorly regulated small gardens, with limited data on its safety. Most available data focuses on pesticide content, but heavy metal contamination remains a hidden risk.

The scientific and technological advancements of the 1950s brought major changes to human life, boosting productivity through the discovery of energy sources, automation, and the use of polymers. By the 21st century, industrial production had increased 50 times, with most of the growth

occurring since 1950. However, this growth led to harmful environmental changes, particularly air pollution. Power plants, factories, chemical plants, and vehicles emit large amounts of CO_2, SO_2, NO_X, CO, chemicals, dust, and heavy metals, altering the atmosphere.

The burning of fossil fuels has caused the largest changes. Between 1860 and 1980, 185 billion tons of carbon were released into the atmosphere, with current emissions at about 5 billion tons annually. In 1910, atmospheric CO_2 levels were 260–270 ppm, rising to 360 ppm by 1985, and potentially reaching 550–600 ppm if current practices continue. These emissions trap heat in the Earth's atmosphere, contributing to the greenhouse effect. In 1986, human-made pollutants contributed to global warming as follows: CO_2 (50%,) CH_4 (19%), PCB (17%), troposphere ozone (8%), N_2O (4%) and stratospheric aerosols (2%).

Based on the current trends and compared to the middle of the previous century, the CO_2 content of the atmosphere will probably double by 2030–2050s, causing a 1.5–4.5 °C temperature rise. Significant parts of SO_2, N_2O, CO_2, CO, and CH_4 appearing in the atmosphere get back and acid sedimentation, moreover, it highly contributes to the acidification of our soils.

As the global population grows, so will the demand for food and food production, leading to increased waste and environmental challenges. Efficient waste management is crucial for protecting environmental, human, animal, and climate health, as well as ensuring sustainable agriculture and agro-industrial processing. To reduce waste, reuse materials, and recycle effectively, circular agricultural production and bio-economic waste management models are key. With ongoing research and innovation, transforming waste into valuable resources and creating a zero-waste agricultural system is achievable.

There is growing interest in finding an effective sewage sludge management strategy within the circular economy. Sewage sludge is challenging to dispose of due to its high concentration of organic, toxic, and heavy metal pollutants, posing significant environmental risks. However, an efficient waste valorization method is converting sludge to energy through anaerobic digestion and gasification processes. While many pre-treatment techniques have been explored to improve sewage sludge as feedstock, limited research has focused on enhancing the fuel quality of the gas produced by anaerobic digestion and gasification.

Land application may be the most economical and energy-efficient method for disposing of or utilizing sewage sludge. However, heavy metals in the sludge can contaminate the soil, affecting crop seed germination and development. Agricultural organic waste, when used as raw material for composting and organic fertilizer production, is considered a renewable resource. This study examines the current state of pollution from composting, as well as the nutritional content and impacts of agricultural organic waste.

Both internal and external elements, such as temperature, moisture content, pH, C/N, and material particle size, have a major impact on the composting process. External influences include ventilation, oxygen supply, and outside additives. Compost maturity is measured using physical, chemical, biological, and new factors. To improve resource utilization of agricultural organic waste, it is necessary to look into the methods of detecting organic matter and phosphorus in compost, as well as their forms of existence and contents, as the transformation process of these materials during the composting process affects the utilization efficiency of compost products. The composting technology has drawbacks, including a lengthy cycle time, emissions of odors and greenhouse gases, and a significant area requirement.

Industrial by-products are increasingly being used in agriculture to improve soil quality, enhance crop yields, and promote sustainable farming. These materials, often considered waste, are repurposed to reduce environmental impact and provide economic benefits.

By-products such as fly ash, phosphogypsum, and steel slag can enhance soil structure, pH balance, and nutrient availability. For instance, lime-based by-products help neutralize acidic soils. Materials like spent grain, molasses, and composted organic wastes serve as fertilizers or nutrient supplements, providing essential elements like nitrogen, phosphorus, and potassium to crops. Treated wastewater and biosolids are used as irrigation water and organic matter sources, respectively. They help conserve water resources and enrich soils with organic carbon and nutrients. Certain industrial by-products, such as neem oil waste and biopesticides, are used to manage pests and diseases in an eco-friendly manner.

Using these by-products reduces landfill waste, minimizes industrial waste, and lowers greenhouse gas emissions. However, risks such as heavy metals, toxins, or pathogens may harm soil health and human safety if not properly treated. Strict regulations and testing are essential for safe application.

Overall, the integration of industrial by-products into agriculture supports circular economy principles, turning waste into valuable agricultural inputs while promoting sustainable farming practices.

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