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ENHANCING SOIL FERTILITY AND CROP PRODUCTIVITY THROUGH DIVERSIFIED COVER CROPPING:

A COMPREHENSIVE ANALYSIS OF GREEN MANURE EFFECTS IN CONTROLLED AND FIELD ENVIRONMENTS

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List of Abbreviations

AMF – Arbuscular Mycorrhizal Fungi
CC - Cover Crops
ANOVA -Analysis of Variance
N - Nitrogen
P - Phosphorus
K - Potassium
pH - Power of Hydrogen (acidity/alkalinity)
NH_4^+ - Ammonium
NO_3^- - Nitrate
N_{min} - Mineral Nitrogen
POXC - Permanganate Oxidizable Carbon
FDA - Fluorescein Diacetate Hydrolysis
EC - Electrical Conductivity
Myco% - Mycorrhizal Colonization Percentage
GLM - General Linear Model
P - Probability Value
η^2 - Partial Eta Squared (Effect Size Measure)
MIX1/MIX2 - Mixed Cover Crop Treatments
FAO - Food and Agriculture Organization
OM - Organic Matter

1. INTRODUCTION AND OBJECTIVES

The vitality and sustainability of agricultural systems hinge on the health of the soil, with cover crops playing a pivotal role in its enhancement. The multifaceted impact of cover crops on soil properties and subsequent main crop biomass production has garnered significant attention in the realm of sustainable agriculture. This thesis explores the influence of different cover crop species and their management as green manure on soil characteristics, microbial activity, mycorrhizal colonization, and the performance of two main crops, corn and pepper, in diverse soil types across three experimental settings.

The vitality and sustainability of agricultural systems hinge on soil health, which plays a fundamental role in ensuring long-term productivity. Among the various strategies to enhance soil quality, cover cropping has emerged as a pivotal sustainable practice. Cover crops not only contribute to soil fertility but also provide a range of ecological benefits, making them integral to modern sustainable farming systems.

This thesis investigates the role of cover crops in improving soil properties, enhancing microbial activity, and boosting the productivity of two main crops—corn and pepper—under different environmental and soil conditions. The research is grounded in the broader goal of promoting sustainable agricultural practices by optimizing cover cropping systems to support soil restoration and long-term agricultural viability.

Scientific and Practical Relevance

Cover cropping is widely recognized for its multifaceted benefits, yet the effectiveness of various cover crop species and their mixtures under diverse conditions remains an area requiring further investigation. The importance and actuality of this thesis lie in its potential to contribute meaningful insights to this knowledge gap. Specifically, the thesis explores how crops cover:

- Improve soil structure and increase organic matter.
- Enhance nutrient cycling and availability.
- Aid in weed and pest management.
- Control soil erosion.
- Contribute to climate change mitigation through carbon sequestration.

By examining these outcomes in a comparative framework across different soils and environments, the research aligns with global efforts to adopt climate-smart and resource-efficient agricultural practices. Moreover, the findings are expected to support practical recommendations for farmers and land managers seeking to improve soil productivity through ecologically sound methods.

In a controlled greenhouse pot experiment, five distinct cover crop species were selected for their varied traits and potential soil health benefits. The cover crops were grown in pots filled with neutral pH sandy soil (Arenosols), a substrate chosen for its agricultural relevance and interactive potential with plant root systems. This meticulous setup aimed to minimize external variability, allowing for an accurate assessment of the cover crops' impact on soil quality and their biomass contribution as organic matter. Parallel to the pot experiment, a field study in Syria's Mediterranean climate introduced additional cover crop species suitable for inceptisol soils. This field experiment aimed to establish an initial understanding of the cover crops' influence on unaltered soil properties.

The synchronization of the field study with the controlled greenhouse experiment provided a broader perspective on the performance of cover crops across varying environmental conditions.

Expanding upon these initial studies, a multi-year pot experiment evaluated the enduring effects of cover crops on different soil types and the subsequent productivity of corn and pepper. Three contrasting soil types Arenosols, Chernozems, and Luvisols—offered a spectrum of physico-chemical contexts to assess the adaptability and cumulative effects of cover cropping. This phase also introduced a detailed examination of soil microbial activity through FDA hydrolysis and quantification of labile carbon via POXC analysis, offering a window into the biological dynamics underpinning soil fertility. These comprehensive studies were underpinned by rigorous analytical procedures.

Biomass production was meticulously measured for both fresh and dry weights, providing a metric for the organic input from cover crops to the soil. The soil microbial activity and mycorrhizal colonization assays gave insights into the biological enhancement of soil health, while the measurement of soil electrical conductivity and concentrations of nitrate and ammonium served as proxies for nutrient availability and soil fertility status. This integrated approach aims to consolidate the role of cover crops as a crucial component of sustainable agriculture, proposing management practices that could revitalize soil systems and enhance crop productivity.

By analyzing the data gathered from these experiments, this thesis will offer comprehensive insights into the advantages and practical applications of cover crops, shaping recommendations for future agricultural strategies.

Objectives:

1. To select specific and variable, **the most common and most-appropriate cover crop-(CC)-species** with different abilities to plant-microbe interrelations. Compare performance, growth and biomass-production and support selection among laboratory and field conditions.

2. To evaluate the performance of the selected cover crops of using **different soil types in two relevant countries (Syria and Hungary)**, with particular soil-characteristics and soil-quality to compare their potential plant-growth-abilities among different environmental conditions.

3. To assess the impact of different cover crops on soil nutrient capacity with a main focus on the nitrogen dynamics. This parameter is reflected in NH_4^+, NO_3^-, and mineral nitrogen (N_{min}) concentrations in used soil types and experimental conditions in both **countries**.

4. To evaluate the influence of cover crop-derived green manure on some **soil health indicators**, specifically to permanganate oxidizable soil-carbon (POXC) parameter and microbial enzymatic activity measured through fluorescein diacetate (FDA) hydrolysis, as potential soil biological parameter.

5. To examine the effects of cover crop management on the biomass (i.e. yield) production of **subsequent main crops** (pepper and corn) as important crops in horti- agri-cultural practices worldwide

Hypotheses:

To guide the analysis of the experimental data, several hypotheses were formulated.

On the basis of literary data we assume, that...:

H-1*: *...there will be significant positive differences among selected cover crops species and its mixtures on the bases of their interrelation with beneficial symbiont microorganisms (considering the double-, simple-, or non-symbiont crops).

H-2: *...the response of cover-crop-performance will be highly dependent on the particular characteristics of main, representative soil types (Arenosols, Chernozems, Luvisols) and its unique soil-health characteristics.*

H-3: *...soil nutrient (Nitrogen) status and capacity of studied soils (assessed as NH_4^+, NO_3^-, N_{min}) will be affected by the different cover crops and mixtures in comparison with the control (without cover crops).*

***H-4*:** *...soil biological and the symbiosis performance indicators (FDA hydrolysis, Myco%) with data about nutrient availability (POXC) will be highly dependent on the used soils and its characteristics, influenced by the different cover crops species and mixtures.*

***H-5*:** *...biomass- and yield-production of subsequent main crops (pepper, maize and lentils) will be dependent, when grown in soils previously treated with different cover crops and or mixtures. Differences will be significant according to the used CC plant-species.*

2. LITERATURE REVIEW

2.1 The Cover Crops (CC) as a Solution to Sustainable Agriculture

2.1.1 Ancient Practices to Modern Resurgence

The utilization of cover crops represents one of humanity's oldest agricultural innovations, with evidence of deliberate cover cropping practices dating back to ancient civilizations. This historical perspective not only illuminates the deep roots of sustainable agriculture but also demonstrates how contemporary cover cropping practices have evolved from empirical observations to scientifically validated approaches.

Ancient Origins and Traditional Knowledge

Historical records show that early agricultural societies valued soil maintenance through cover cropping. In ancient Rome, Cato the Elder, in De Agri Cultura (c. 160 BCE), recommended planting lupines and vetches to “make the soil better,” and refresh the soil between grain plantings while Varro, in (37 BCE), advised using legumes to “enrich the soil as would the best manure.” These observations reflect an early understanding of soil fertility enhancement through biological nitrogen fixation (McNeill & Winiwarter, 2004). These writings reflect an empirical understanding of what is now known as biological nitrogen fixation, long before it was scientifically explained.

In ancient China, crop rotation systems during the Zhou Dynasty (c.1046 – 256 BCE) included green manures such as Azolla, a nitrogen-fixing aquatic fern grown in rice paddies. The 6th-century agricultural text Qi Min Yao Shu described incorporating green manures to “restore the soil’s vigor,” indicating a systematic approach to soil renewal (Bray, 1984).

The use of crops, now commonly referred to as cover crops (CC), dates back over millennia. Ancient civilizations recognized their importance for enhancing the growth of cultivated crops. An example of early cover cropping practices can be seen in the Native American "Three Sisters" method, where corn, edible broad beans, and squash were grown together. where broad beans (a legume) provided nitrogen benefits while corn offered structural support and squash suppressed weeds through ground coverage. This system, developed over thousands of years, demonstrates sophisticated ecological understanding that predates modern scientific explanations of plant interactions and soil processes. This practice underlined the benefits of crop diversity and laid the groundwork for the synergy of mixed species in cover cropping today (Groff, 2015).

Medieval and Early Modern Developments

The medieval three-field rotation incorporated fallow periods with volunteer vegetation functioning as primitive cover crops (Mazoyer and Roudart, 2006). By the late Middle Ages, this evolved to include deliberate planting of nitrogen-fixing legumes during fallow periods (Campbell, 2000). The Agricultural Revolution brought more systematic approaches, particularly the Norfolk four-course rotation, which replaced fallows with turnips and clover, maintaining year-round soil coverage while providing fodder for livestock (Overton, 1996).

In North America, George Washington and Thomas Jefferson experimented with cover crops and green manures, documenting their observations and promoting these practices (Rasmussen, 1989). By the 19th century, scientific explanations emerged for benefits farmers had observed for millennia.

Justus von Liebig's work on plant nutrition and Jean-Baptiste Boussingault's research on nitrogen fixation provided scientific understanding of how cover crops enhanced soil fertility (Smil, 2001).

Decline During the Industrial Agricultural Era

Cover cropping declined significantly during the 20th century with the rise of industrial agriculture due to several factors:

- Synthetic fertilizers following the Haber-Bosch process provided a quick alternative to biological nitrogen fixation (Smil, 2001)
- Agricultural mechanization favored simplified cropping systems and monocultures (Lal, 2015)
- Effective herbicides reduced concerns about weed pressure during fallow periods (Triplett and Dick, 2008)
- Economic pressures and policies incentivized maximum production of commodity crops with little consideration for soil health (Carlisle, 2016)
- Agricultural education is increasingly focused on chemical inputs rather than ecological management practices (Danbom, 1995)

Contemporary Resurgence

In the late 20th century and accelerating into the 21st, cover cropping was widely used. However, with the advent of selective pre- and post-emergent herbicides, the practice of growing cover crops declined. In recent years, there has been a resurgence of interest in cover crops, driven by the increased focus on soil quality and the desire to reduce chemical inputs in agriculture. This renewed interest stems from the recognition of cover crops' benefits, such as erosion control, soil health improvement when research demonstrated that soil biological activity, structure, and organic matter all enhanced by cover crops were fundamental to sustainable productivity (Karlen et al., 2003). Moreover, of the water infiltration enhancement, weed suppression, pest and disease control, and biodiversity increase (Sarep, 2017). Recent research by (Lal & Stewart 2023) emphasizes that soil health management through cover cropping not only improves agricultural productivity but also contributes significantly to climate change mitigation through enhanced carbon sequestration and reduced greenhouse gas emissions. Today, the implementation of cover crops is tailored to specific agricultural objectives and conditions. (Lehmann et al., 2020) have proposed an updated framework for soil health assessment that integrates biological, chemical, and physical indicators with ecosystem service delivery, suggesting that cover crop impacts should be evaluated not only through traditional soil tests but also through their contributions to broader ecological functions.

Factors such as site specification, timing, and cropping history play a critical role in choosing the most appropriate cover crop species for a given system. This strategic approach to cover cropping highlights its evolution from traditional practices to a more nuanced, science-based component of modern sustainable agriculture (Grove & Pena-Yewtukhiw 2017). This evolutionary trajectory reflects a remarkable cycle of agricultural knowledge practices developed through traditional observation have been validated and refined through scientific investigation, creating more sophisticated applications of age-old principles (Gliessman, 2014).

2.1.2 Soil structure improving functions of Cover crops

Cover crops, an integral component of sustainable agriculture, are non-cash crops planted primarily for soil coverage and enrichment, rather than for direct harvest (Quintarelli et al., 2022). These crops are extensively used in both farming and gardening, offering a sustainable alternative to traditional practices. Cover crops serve multiple functions: they manage soil erosion, enhance soil fertility, and improve overall soil quality (Plastina et al., 2018).

Soil structure exists in a hierarchical organization, from micro-aggregates (< 250 μm) to macro-aggregates (> 250 μm), with distinct formation processes at each scale (Tisdall and Oades, 1982). Cover crops influence this hierarchy through physical entanglement by roots and fungal hyphae, chemical binding by organic compounds, and biological "glues" from microbial activity (Bronick and Lal, 2005). Soil structure responds to both degradative forces (raindrop impact, tillage, compaction) and regenerative processes (root growth, organic matter accumulation, microbial activity). Cover crops enhance the regenerative processes, creating a more favorable balance that promotes structural development and resilience (Kravchenko et al., 2019).

Different cover crop species influence soil structure through their unique root architectural patterns, each contributing in complementary ways to aggregation, porosity, and biological activity (Bodner et al., 2014). Fibrous-rooted species such as grasses and cereals (e.g., *Secale cereale*) develop dense, branching root networks that physically entangle soil particles, promoting the formation and stabilization of macroaggregates (Oades, 1984). These fine roots also create numerous small biopores upon decomposition, enhancing micropore connectivity and facilitating water movement throughout the soil profile (Bodner et al., 2014). Empirical studies using X-ray computed tomography have demonstrated 30-45% greater pore connectivity in soils following fibrous-rooted cover crops compared to fallow controls (Burr-Hersey et al., 2017). The high surface area of fibrous roots provides extensive habitat for rhizosphere microorganisms, stimulating microbial activity that further supports aggregation through biological binding agents (Haynes & Beare, 1997).

In contrast, taproot species such as *Raphanus sativus* penetrate compacted soil layers, creating deep macropores that persist after root decay. This “biological drilling” effect reduces soil strength by 25-35% at depths of 15-30 cm and improves root zone accessibility for subsequent crops (Williams & Weil, 2004; Chen & Weil, 2011). This is particularly effective in alleviating subsurface compaction that conventional tillage often fails to address (Cresswell & Kirkegaard, 1995). Subsequent crop roots have been shown to follow these biological channels, with studies reporting 40–60% of main crop roots exploiting taproot-created pores (Han et al., 2015). Cover crop mixtures that combine both fibrous and taproot architectures frequently result in superior improvements in soil structure, as they simultaneously enhance surface aggregation and subsurface porosity (Wittwer et al., 2017).

Leguminous cover crops, which exhibit intermediate root forms with branched taproots and some fibrous development, contribute more indirectly by fostering soil biological activity rather than primarily through mechanical soil alteration (Materechera et al., 1992; Haynes & Beare, 1997; Biró, 2006). Their nitrogen-rich exudates and residues stimulate microbial biomass and enzymatic activity, leading to increased production of microbial polysaccharides and glomalin—biological “glues” that aid aggregate formation (Bronick & Lal, 2005).

Comparative studies have shown 50–70% higher enzyme activities in soils under legumes than in those under non-legume cover crops (Bandick & Dick, 1999). These biologically mediated processes make legumes critical players in promoting stable soil structure and long-term fertility. Beyond physical architecture, roots influence soil structure through biochemical pathways involving root exudates (Jones et al., 2009), which play a critical role in soil structural development by chemically binding particles and fueling microbial activity in the rhizosphere. Grasses release higher quantities of exudates rich in polysaccharides and phenolics, enhancing aggregate stability directly, while legumes contribute more through stimulating microbial processes (Jones et al. 2009; Haynes and Beare 1997). These biochemical interactions complement physical root architecture, making exudation an essential mechanism in cover crop-mediated soil improvement.

In the realm of sustainable agriculture, the health of our soil is paramount, directly influencing crop growth and global food security. As the world population burgeons, the demand for food intensifies, pressing upon the limited arable land. This scenario is further exacerbated by climate change, which variably affects crop yields. Against this backdrop, innovative and sustainable farming practices are critical. One such practice garnering widespread attention is the use of cover crops (FAO, 2017; Kremen et al., 2012; Bergtold et al., 2017). Recent research by (Chaplot & Smith, 2023) estimates that widespread adoption of cover cropping could sequester between 0.12 and 0.32 Gt C per year globally, representing a significant contribution to agricultural climate mitigation strategies while simultaneously building resilience to extreme weather events. One of the primary ways cover crops improve soil structure is by increasing soil organic matter (SOM). As cover crops grow, they contribute biomass both above ground and below ground. This organic matter, upon decomposition, enhances soil aggregation, creating a more stable and porous soil structure (Six et al., 2000).

The improved aggregation leads to better water infiltration, reducing runoff and soil erosion (Drinkwater et al., 1998). The extensive root systems of some cover crops, particularly those with deep taproots like radishes or fibrous root systems like grasses, further enhance soil structure. These roots create channels in the soil, improving aeration and water movement. This is particularly important in soils with a clay-enriched subsoil, such as Luvisols, where compaction can be a limiting factor (White and Weil, 2011; Williams and Weil, 2004). The role of cover crops in enhancing Chernozem soils, known for their excellent structure, was also highlighted. Furthermore, cover crops protect the soil surface from the impact of raindrops, preventing soil crusting and maintaining infiltration rates (Blanco-Canqui & Lal 2009). The combined effect of increased SOM, improved aggregation, and root activity results in a more resilient soil structure that can better withstand compaction and erosion, ultimately benefiting the growth of subsequent crops (Kravchenko et al, .2012).

Living cover crop canopies protect the soil surface from raindrop impact, which can disintegrate aggregates and form surface seals (Zuazo and Pleguezuelo, 2008). Research has demonstrated that cover crops with 60% or greater canopy coverage reduce kinetic energy reaching the soil surface by 70-90% (Folorunso et al., 1992). Long-term studies in erosion-prone regions have shown that consistent cover crop use can maintain surface aggregate stability at 40-60% higher levels than conventionally managed soils without cover (Kaspar et al., 2001). Cover crops modify soil microclimate, creating conditions more favorable for structural development (Dabney et al., 2001). Living canopies moderate soil temperature extremes, reducing stresses of freezing-thawing and wetting-drying cycles that can disrupt aggregates (Steele et al., 2012). CC also influences soil moisture dynamics, generally increasing infiltration while reducing evaporation (Dabney et al., 2001).

Long-term monitoring has shown that soils under consistent cover crop management experience 25-45% fewer extreme wetting-drying events than bare soils (Steele et al., 2012).

The study by (Kaspar & Bakker 2015) significantly contributes to our understanding of cover crops' role in promoting soil health and mitigating environmental impacts, with a particular focus on water quality and soil sustainability. Their research underscores the efficacy of cover crops in reducing NO_3 leaching, a critical factor in environmental conservation. Highlighted in a related meta-analysis, cover crops have been shown to decrease NO_3 leaching losses by up to 70% across diverse soil types and climatic conditions, demonstrating their vital role in sustainable agricultural practices, as well as CC represents a cornerstone practice in agroecological transitions, noting that farms implementing diverse cover crop rotations typically reduce synthetic input dependency by 30-50% while maintaining or improving yields over a 3-5 year transition period (Altieri et al., 2025).

2.1.3 The effects of CC on Soil Nutrient Status

Cover crops, also known as catch crop plants in some contexts, offer a multifaceted solution for soil health improvement and nutrient provision. Growing between main crop cycles, these crops contribute significantly to enhancing health improvement and nutrient provision and increased nutrient provision. The benefits include improved nutrient availability and enhanced cycling of essential elements like nitrogen, phosphorus, and potassium (Begum et al., 2019; Dabney et al., 2001; Drinkwater et al., 1998; Quintarelli et al., 2022; Zabel, 2020).

Furthermore, the strategic selection and rotation of diverse cover crops such as legumes, non-legumes, brassicas, and grasses can lead to optimized soil health benefits; Elving into the specifics, cover crops can be categorized based on their symbiotic relationships and contributions to soil health. For instance, legumes (e.g., broad bean and vetches), non-legumes (e.g., spinach and mustards), brassicas (e.g., radishes and turnips) and grasses (e.g., oat and wheat) (FAO, 2012). The interaction between cover crops and different soil types influences nutrient dynamics. For instance, Legume Cover crops are renowned for their dual symbiotic relationships; each category has different characteristics and provides unique benefits. Are highly valued as cover crops due to their ability to fix atmospheric nitrogen into the soil, thereby enhancing soil fertility. This process, known as nitrogen fixation, is facilitated by symbiotic bacteria in the roots of legumes. Broad beans, a common type of legume used as a cover crop, are effective in improving soil structure and nutrient content (Biró et al., 2000). They are particularly useful in crop rotations to replenish nitrogen depleted by heavy-feeding crops (Altieri & Nicholls, 2005). This process enriches the soil with plant-available nitrogen, reducing the need for synthetic nitrogen fertilizers. A comprehensive meta-analysis by (Daryanto et al., 2020) examining over 300 studies revealed that cover crops can increase subsequent cash crop yields by an average of 15.5% while simultaneously reducing nitrogen leaching by up to 40% and enhancing soil organic carbon by 12.8% compared to bare fallows.

Agroecology and the Search for a Truly Sustainable Agriculture., they not only fix atmospheric nitrogen, enriching the soil with this crucial nutrient, but also engage in symbiosis with mycorrhizal fungi, thus enhancing nutrient uptake and soil health (Paolo & Mazzoncini, 2017; Collins et al., 2007). Furthermore, cover crops can scavenge residual nutrients from deeper soil layers, preventing leaching and making them available to the next crop (Thorup-Kristensen et al., 2003). This is particularly important for mobile nutrients like nitrates, which can be lost through leaching, contributing to water pollution. The decomposition of cover crop biomass also releases other nutrients, such as phosphorus and potassium, back into the soil, further enhancing fertility (Fageria & Baligar, 2005). Furthermore, incorporating legumes in a cropping system may provide a variety of indirect benefits, beside the direct biological N-supply of crops (Murphy-Bokern et al., 2017).

Nitrogen (N) is among the most responsive soil nutrients to cover crop (CC) management, with its cycling significantly affected by species selection, functional traits, and environmental conditions (Thorup-Kristensen et al., 2003). Cover crops influence nitrogen dynamics primarily through three pathways: biological nitrogen fixation, nitrogen scavenging, and nitrogen release from residues each contributing differently depending on cover crop type and system design. The amount of N fixed is highly variable, depending on species, growth duration, and soil conditions. Under optimal circumstances, legumes such as *Vicia faba* can fix 150–200 kg N/ha, while lower-yielding species typically fix 50–80 kg N/ha (Peoples et al., 2015). Meta-analyses estimate an average of 133 kg N/ha fixed by winter legumes across diverse agroecosystems (Tonitto et al., 2006). Research has shown that a diverse mixture of cover crops can lead to greater soil health benefits, including improved soil structure, nutrient cycling, and weed suppression, compared to the use of a single cover crop species (Snapp et al., 2005; Teasdale, 2017). As well as Oats are excellent for soil erosion control and weed suppression. Their dense root systems help in improving soil structure and organic matter content.

Oats, being a cool-season crop), can be grown in the off-season to cover bare soil, thus reducing erosion and runoff. They also serve as a catch crop for residual nutrients, preventing them from leaching into waterways (Snapp et al., 2005). Non-leguminous cover crops, particularly grasses and brassicas, are effective nitrogen scavengers, capturing residual mineral N from the soil profile and reducing losses via leaching or denitrification (Thorup-Kristensen et al., 2003). Non-symbiotic crops, such as mustard, have a different yet vital role in agricultural systems. They are instrumental in breaking pest and disease cycles and can be effectively used in crop rotations to maintain soil health and enhance productivity. Mustard, with its biofumigant properties, offers a natural method for pest and disease control, thus reducing reliance on chemical pesticides (Collins et al., 2007), (Larkin & Griffin, 2007).

In addition to nitrogen, cover crops play a pivotal role in regulating phosphorus (P) dynamics, an increasingly valuable function amid concerns over finite global P resources and nutrient runoff into water bodies (Hallama et al., 2019). While nitrogen benefits are often more immediate and visible, the influence of cover crops on phosphorus is equally critical for long-term soil fertility and nutrient efficiency. Legumes and some non-legumes also stimulate phosphatase enzyme activity, which breaks down organic P compounds into plant-available forms (Richardson et al., 2009). Mycorrhizal associations commonly formed by legumes and grasses—further expand the root zone's access to phosphorus, effectively increasing uptake from otherwise inaccessible soil layers (Kabir & Koide, 2000).

Cover crops also influence calcium, magnesium, and sulfur dynamics, though these effects have received less research attention (Blanco-Canqui et al., 2015). Deep-rooted cover crops can access subsoil reserves of these nutrients and redistribute them to surface layers, improving availability to subsequent crops with shallower root systems (Blanco-Canqui et al., 2015). Cover crops can enhance micronutrient availability through several mechanisms, with effects varying by nutrient, cover crop species, and soil conditions (Soltangheisi et al., 2018). Beyond specific nutrient effects, cover crops influence broader soil chemical properties that affect nutrient availability and cycling (Kim et al., 2020). Soil pH may be modified by cover crops through several mechanisms, including differential cation-anion uptake, nitrogen fixation processes, and organic acid exudation (Kim et al., 2020)

2.1.4 The effects of CC on plant growth and development

The improvements in soil structure and nutrient status resulting from cover crop cultivation have direct positive impacts on subsequent plant growth and development. Enhanced soil environment allows for better root penetration, water infiltration, and nutrient uptake, crucial for optimal plant growth (Kaspar & Bakker, 2015). Furthermore, cover crops can suppress weeds, pests, and diseases which reduces competition for resources and enhances main crop performance (Larkin & Griffin, 2007). The residue from cover crops also helps regulate the microclimate around plants, maintaining soil moisture and tempering temperature extremes (Miguez et al., 2016), After the implementation of cover crops is, a strategic decision that hinges on the benefits accrued to soil health, nutrient dynamics, pest and disease management, and overall climatic adaptability. In this context, pepper (*Capsicum spp*.) and corn (*Zea mays*) emerge as prime candidates, each benefiting distinctly from the preceding cover crop regimes, thereby enhancing agricultural productivity and sustainability.

Peppers (*Capsicum spp*.) demand fertile soils and greatly benefit from the improved soil structure and enhanced organic matter levels contributed by cover crops. Legumes, such as clover or vetch, are particularly beneficial when planted before peppers. They fix atmospheric nitrogen, enriching the soil with this critical nutrient, thereby reducing the reliance on synthetic fertilizers and lessening environmental impacts (Clark, 2007). Additionally, cover crops like rye can suppress nematode populations, a common pest for peppers, and the incorporation of cover crops can stimulate beneficial microorganisms, promoting a healthier soil ecosystem that combats pathogens (Teasdale et al., 2017).

Certain cover crop species, particularly those in the Brassicaceae family, can directly suppress soil-borne pathogens through the release of allelopathic compounds such as glucosinolates and their breakdown products (Larkin et al., 2010). Cover crops create complex effects on pest and disease pressure that can significantly influence main crop performance (Lundgren and Fergen, 2011). Beneficial insect populations typically increase under cover crop systems, enhancing biological control of crop pests (Lundgren and Fergen, 2011). The residue from these crops also helps regulate the microclimate around pepper plants, maintaining soil moisture and tempering temperature extremes, which is crucial for the growth of peppers. Furthermore, this ground cover minimizes weed competition; ensuring peppers have less competition for essential resources like nutrients and water (Montgomery, 2007).

Similarly, corn *(Zea mays*) on the other hand, benefits from the deep rooting systems of specific cover crops, such as radishes or deep-rooted legumes, which alleviate soil compaction and enhance soil structure. This improvement is pivotal for corn's root penetration and water infiltration, crucial for nutrient and water uptake (Lal, 2004). Cover crops preceding corn can also boost nutrient cycling, particularly nitrogen availability, through the decomposition of leguminous cover crops, which releases nitrogen and other nutrients in a form readily available to the corn crop. This process can lead to improved corn yields and a reduced need for chemical fertilizers (Perrone, S et al., 2020).

Additionally, the root systems of cover crops play a vital role in reducing soil erosion, a significant concern for cornfields prone to loss through wind and water erosion. The residue from these crops helps retain soil moisture, offering a more stable water supply for corn, especially beneficial in areas facing dry spells or where water conservation is imperative (Blanco-Canqui & Lal 2009) .Moreover, cover crops serve multiple functions: they manage soil erosion, enhance soil fertility, and improve overall soil quality, which collectively contribute to a more favorable environment for plant growth.

2.2 Selection of cover crops by different characteristics

2.2.1 The Nitrogen-Fixers

The use of nitrogen-fixing cover crops, particularly legumes, is a cornerstone of sustainable agriculture. Early examples of such practices can be seen in the Native American "Three Sisters" method, where the intercropping of corn, broad beans, and squash provided a balance of nutrients, with broad beans fixing atmospheric nitrogen (Mt. Pleasant, 2016). This ancient practice laid the groundwork for understanding the synergy of mixed species in cover cropping. Leguminous cover crops, such as broad bean (*Vicia faba*), vetch (*Vicia spp*.), and clover (*Trifolium spp*.), are highly valued for their ability to enhance soil fertility through biological nitrogen fixation. This process, facilitated by symbiotic bacteria (rhizobia) residing in root nodules, converts atmospheric nitrogen gas (N_2) into ammonia (NH_3), which is then assimilated by the plant and eventually becomes available to other plants upon decomposition (Peoples et al., 2009). The nitrogen fixed by legumes can significantly reduce the need for synthetic nitrogen fertilizers, which are energy-intensive to produce and can have negative environmental impacts.

This dual symbiosis renders legumes particularly valuable in agricultural rotations, contributing significantly to soil fertility and reducing dependence on synthetic fertilizers. Notably, broad bean crops exhibited the highest EC values within the luvisol environment. This finding aligns with previous research by (Smith et al., 2018), who reported that leguminous plants, such as broad beans, can sometimes influence soil ion concentrations and EC due to their root exudates and nutrient uptake patterns. The inclusion of legumes in crop rotations replenishes nitrogen depleted by heavy-feeding crops like corn, contributing to a more sustainable and closed-loop agricultural system. Legume cover crops are renowned for their dual symbiotic relationships; they not only fix atmospheric nitrogen, enriching the soil with this crucial nutrient, but also engage in symbiosis with mycorrhizal fungi, thus enhancing the nutrient uptake and additionally the soil health parameters.

2.2.2 The P-Mobilizers Ability

Phosphorus (P) is another essential nutrient for plant growth, often limited in agricultural soils due to its low solubility and tendency to form stable complexes with soil minerals. Certain cover crops, through their association with arbuscular mycorrhizal fungi (AMF), play a crucial role in mobilizing and making phosphorus more available to plants (Smith & Read, 2008). AMF forms a symbiotic relationship with the roots of most terrestrial plants, extending the root system through vast networks of hyphae that can explore a larger volume of soil than roots alone. These hyphae produce enzymes and organic acids that can solubilize phosphorus from mineral forms, making it accessible to the plant. In return, the plant provides fungi with carbohydrates produced through photosynthesis (Parniske, 2008). The introduction of cover crops into agricultural systems has been shown to positively influence AMF populations, increasing their diversity and abundance, Specific cover crops, such as buckwheat (*Fagopyrum esculentum*) and brassicas (*Brassica spp.),* have been shown to be particularly effective at mobilizing phosphorus, although the mechanisms may differ (Smith et al., 2011).

Single symbiosis cover crops, like certain brassicas, interact primarily with mycorrhizal fungi without the nitrogen-fixing ability. These species, while not contributing directly to nitrogen enrichment, play a significant role in soil health. For instance, brassicas with their deep rooting systems are known to aid in soil aeration and structural improvement, which is crucial for root growth and water infiltration, indirectly affecting phosphorus availability (Snapp et al., 2005).

2.2.3 The Role of Symbiosis and Other Important Aspects

Within agricultural ecosystems, symbiotic relationships between plants and soil microorganisms play a crucial role in nutrient cycling, soil structure development, and overall system resilience. Cover crops can be strategically selected based on their symbiotic capabilities to address specific soil management objectives. The symbiotic relationships between cover crops and soil microorganisms, particularly mycorrhizal fungi, play a vital role in enhancing soil health and plant productivity. Cover crops can be categorized based on their symbiotic relationships: Double Symbiotic Plants those that form associations with both nitrogen-fixing bacteria and mycorrhizal fungi Leguminous cover crops such as broad bean (*Vicia faba*), lentil (*Lens culinaris*). The dual symbiotic capability of leguminous cover crops creates a synergistic effect that enhances both plant growth and soil health. (Püschel et al., 2017) demonstrated that the co-occurrence of rhizobial and mycorrhizal symbioses in legumes results in greater nutrient acquisition efficiency and biomass production compared to plants with single or no symbiotic relationships. This makes double symbiotic cover crops particularly valuable in sustainable agricultural systems seeking to reduce external input while maintaining productivity. Single Symbiotic Plants those that interact primarily with mycorrhizal fungi (e.g., certain brassicas) while these plants cannot fix atmospheric nitrogen, their association with AMF significantly enhances their ability to access soil phosphorus and other immobile nutrients. (Higo et al., 2020). These symbiotic interactions enhance nutrient uptake, improve soil structure, and contribute to overall ecosystem resilience (Larkin & Griffin, 2007). For example, brassicas, while not fixing nitrogen, have deep rooting systems that aid in soil aeration and structural improvement. Oats, with their dense root systems, are excellent for soil erosion control and weed suppression, improving soil structure and organic matter content, and Non-Symbiotic Plants (e.g., some mustards) generally do not form significant symbiotic relationships with either nitrogen-fixing bacteria or mycorrhizal fungi (Snapp et al., 2005). These plants produce glucosinolates and other compounds that, upon decomposition, release isothiocyanates with biofumigant properties that can suppress soil-borne pathogens but may also inhibit beneficial soil organisms including AMF (Alcántara, C et al., 2009).

Non-symbiotic crops like some mustards have a different yet vital role, breaking pest and disease cycles and can be effectively used in crop rotations to maintain soil health and enhance productivity with its biofumigant properties, offering a natural method for pest and disease control. In addition to their symbiotic relationships, the physical characteristics of cover crop root systems play a significant role in improving soil health. cover crops with deep taproots, such as radishes, can alleviate soil compaction, creating channels that improve water infiltration and aeration (Williams & Weil, 2004). Fibrous root systems, common in grasses like rye and oats, are effective at binding soil particles together, preventing erosion and improving soil aggregation (Blanco-Canqui & Lal, 2009).

The diversity of root architecture in cover crop mixtures contributes to a more heterogeneous soil environment, promoting a wider range of beneficial soil organisms and enhancing overall soil function. Using mixtures of cover crops, often referred to as cover crop cocktails, has gained popularity in sustainable agriculture for its multifaceted benefits, exceeding what single-species cover crops can offer. This approach synergizes the unique advantages of various cover crops, addressing multiple agricultural needs simultaneously like Enhanced Soil Health: Mixing legumes with grasses or brassicas can improve soil health more comprehensively. Legumes fix nitrogen, enriching the soil for subsequent crops, while grasses and brassicas improve soil structure and organic matter content (Singh et al., 2023). This combination leads to a balanced improvement in soil fertility, structure, and aeration (Snapp et al., 2005), and Increased Biodiversity: Diverse cover crop mixtures support a wider range of soil organisms and above-ground biodiversity, enhancing ecosystem services like pollination and pest control. This biodiversity can lead to more resilient agricultural systems capable of withstanding pests, diseases, and climatic variations (Altieri & Nicholls, 2005).

Different cover crops can suppress weeds and pests in complementary ways. For example, grasses can outcompete weeds through quick ground cover, while certain brassicas have biofumigant properties that control soil-borne pests and diseases. The combined effect can significantly reduce the reliance on chemical herbicides and pesticides (Larkin & Griffin, 2007), over crops reduce pesticide contamination by enhancing microbial activity in the rhizosphere, which accelerates pesticide degradation in the topsoil. Additionally, their root systems help retain pesticide residues in biologically active zones, limiting their leaching into groundwater (Vandevoorde et al.,2025), also planting a mixture of cover crops reduces the risk of total crop failure due to specific pests, diseases, or adverse weather conditions. If one species in the mixture fails, others may thrive, ensuring that the soil remains covered and benefits like erosion control and nutrient capture are still achieved (Liebman & Schulte, 2015).

2.3 CC and Their Application

2.3.1 Differences among Soil Characteristics

Understanding the local agricultural context is crucial for interpreting and applying the findings of this thesis, particularly given the experimental setups in both Hungary and Syria. The effectiveness of cover crops is significantly influenced by the inherent characteristics of the soil. The three main soil types used in this study in Hungary are Arenosols, Luvisols, and Chernozems, each of which exhibits distinct physical and chemical properties, and the soil used in Syria was Inceptisoil.

Sandy (Arenosols): are characterized by their high sand content, often found in arid or semi-arid regions. They have low water and nutrient retention capacities due to the large pore spaces between sand particles. This leads to rapid drainage and can make them challenging for crops that require consistent moisture. However, their loose structure allows for excellent root penetration and aeration. pH: Typically, acidic to slightly acidic. Soil Organic Matter: Generally low due to rapid decomposition and leaching. Texture: Predominantly sandy, leading to high porosity and fast drainage. Nutrient Availability: Often limited, requiring regular amendments to support crop growth. Suitable for crops that prefer well-drained conditions, such as root vegetables and certain legumes (Brady & Weil, 2016), sandy soils advantageous for crops that prefer well-drained conditions and are sensitive to root waterlogging, such as root vegetables, certain legumes, and tuber crops. Their quick warming in the spring and good aeration are beneficial for early-sown crops.

Luvisols are prevalent in temperate climates, featuring a clay-enriched subsoil. They are well-structured soils, known for their fertility and high nutrient-holding capacity. Luvisols have a good water retention capacity, making them suitable for a wide range of agricultural uses. Their depth and fertility support diverse crop production, including cereals, vegetables, and tree crops. Luvisols are prevalent in temperate climates, with a clay-enriched subsoil. They are fertile, with high nutrient-holding capacity and good water retention, making them suitable for a wide range of agricultural uses (IUSS Working Group WRB, 2022). pH: Slightly acidic to neutral, conducive to a wide range of agricultural crops. Soil Organic matter: Moderate to high, benefiting from the clay's nutrient retention capabilities. Texture: Characterized by a clay-enriched subsoil with good structure and aeration. Nutrient Availability: High, due to the soil's ability to retain nutrients and water, making it suitable for intensive agriculture. Luvisols support a broad range of crops, including cereals, legumes, and oilseed crops, due to their balanced moisture and nutrient retention properties (Blume et al., 2016).

Chernozem soils are highly fertile, with a deep, dark, humus-rich topsoil, excellent structure, and moisture retention capabilities. They are ideal for growing cereals, sugar beets, and sunflowers (IUSS Working Group WRB, 2022). Chernozem soils are best utilized for high-yielding cereal crops, such as wheat, maize, and barley, due to their high organic matter content and water retention. They are also excellent for oilseed crops and sugar beets, which benefit from the soil's rich nutrient profile. pH: Neutral to slightly alkaline, ideal for most crops. Soil Organic Matter: Very high, with a thick, dark topsoil rich in humus. Texture: Loamy to clay-loam, providing excellent water retention and aeration. Nutrient. Availability: Extremely high, supporting high yields of a variety of crops without extensive fertilization.

Chernozem soils are best for high-yielding cereal crops and oilseed crops, benefiting from the soil's rich nutrient profile (Brady & Weil, 2016). Recent studies and analyses offer valuable perspectives on the management and potential of Sandy Arenosols, Luvisols, and Chernozem soils, highlighting innovative practices and challenges in agricultural sustainability.

(Francis & Tóth, 2022) emphasize the role of cover cropping in Luvisols, enhancing soil structure and fertility, thereby increasing crop yields significantly. This approach, as reported in the Journal of Sustainable Agriculture, underscores the importance of soil-specific management strategies to optimize agricultural output. Comparative analyses by (Blanco-Canqui & Lal 2009) delve into the intrinsic differences between soil types, particularly focusing on water retention and nutrient cycling. Their work in Soil Science Annual reveals that Chernozem's organic matter richness markedly benefits water retention, guiding farmers towards crop and management selections that align with soil properties. Concurrently, the impact of climate change, as discussed by (Marzen et al., 2019) in Global Environmental Change, accentuates the vulnerability of Sandy Arenosols to erosion, prompting a reevaluation of conservation strategies to protect these vital soil resources. (Kravchenko et al., 2012) as a method to conserve organic matter and enhance soil carbon sequestration have highlighted sustainability in agriculture, particularly through no-till farming in Chernozem soils. Published findings in the Journal of Soil and Water Conservation advocate for the adoption of such practices widely to ensure long-term soil health and productivity. Additionally, the (FAO, 2019) outlines practical soil conservation techniques, including terracing and windbreak establishment, crucial for mitigating erosion in Sandy Arenosols and preserving agricultural land. Looking towards the future, (UNCCD, 2022) underscore the necessity for research into drought-resistant crops for Sandy Arenosols, a critical endeavor to secure food production under the challenges of climate change and water scarcity. (Fekete et al., 2022) echo this in Precision Agriculture, who demonstrate the efficacy of soil moisture sensors and precision irrigation in managing water use in Luvisols, offering a path towards more sustainable and efficient agricultural practices. Policy and economic frameworks also play a pivotal role in fostering sustainable soil management, as explored by (Bonfante et al., 2019). Their review suggests that subsidies for green technology adoption can significantly promote environmental stewardship while enhancing the productivity of fertile soils such as Chernozem.

These challenges are not limited to global examples; they strongly resonate with the conditions found in parts of Syria.

Syria's diverse geography and climate contribute to a variety of soil types, with the USDA Soil Taxonomy providing a useful framework for classification (Soil Survey Staff, 2014). While several soil orders are present, Inceptisols are particularly significant, covering approximately 24% of the country's total area. These soils widely distributed along the northern border with Turkey and forming transitional zones between the coastal mountains and the more arid eastern regions. They are also prevalent in the southwestern part of the country.

Inceptisols are characterized by their limited horizon development, meaning they are relatively young soils that still largely reflect the properties of their parent material (Khresat, S, 2005). Their agricultural potential varies, but they can be productive with appropriate management, especially in areas with more favorable moisture regimes. The presence of calcium carbonate (as indicated by 'Calci' in Calcixerollic) can influence nutrient availability and pH, while the moisture regime implies dry summers and moist winters, a typical Mediterranean climate pattern (Ortega et al., 2016). Beyond Inceptisols, other notable soil orders in Syria include Aridisols (the most widespread, covering 54%, found in arid and semi-arid regions), Entisols (14%, often on steep slopes or floodplains), Vertisols (1%, characterized by swelling clays), and less common Mollisols and Alfisols (Mohammed et al., 2020).

Understanding these characteristics, especially for Inceptisols, is fundamental for developing effective and sustainable agricultural management practices tailored to the Syrian context, guiding decisions on crop selection, irrigation, fertilization, and soil conservation measures.

One of our experiments on this design of this thesis strategically combines controlled pot experiments in Hungary with field experiments in Syria. This dual approach is critical for generating robust and broadly applicable findings. The Hungarian pot experiments, conducted under highly controlled conditions, allow for a precise investigation into the fundamental mechanisms of cover crop effects on soil properties and plant growth, minimizing external variability. Conversely, the Syrian field experiments provide invaluable insights into the practical applicability and performance of these practices within a real-world agricultural setting, accounting for complex environmental interactions and local challenges. By integrating data from both controlled and natural environments, this research aims to bridge the gap between theoretical understanding and practical implementation, offering a comprehensive perspective on sustainable agricultural practices.

The outcomes are expected to inform locally adapted soil management strategies that enhance resilience under climate stress. Ultimately, this research contributes supports the long-term sustainability of Syrian agriculture. The following table summarizes the key differences and similarities in their experimental environments:

Table 1. Comparison of Experimental Conditions: Hungary (Pot Experiment) vs. Syria (Field Experiment)

Feature	Hungary (Pot Experiment)	Syria (Field Experiment)
Environment	Highly Controlled (Greenhouse)	Uncontrolled (Open Field)
Soil Type	Sandy Arenosols; typically, well-characterized.	Diverse, including extensive Inceptisols; often calcareous, shallow, and subject to significant degradation (erosion, low organic matter, salinity); highly heterogeneous
Climate	Simulated or optimized conditions; temperature, humidity, and light precisely regulated.	Arid to semi-arid; characterized by significant rainfall variability, humidity, recurrent droughts, and extreme temperatures.
Variability	Low; high internal validity and replicability due to controlled conditions.	High; reflects natural environmental fluctuations and inherent soil heterogeneity, providing external validity
Focus	Mechanistic understanding of plant-soil interactions, nutrient dynamics, and initial growth responses under ideal or specific conditions.	Practical applicability, validation of controlled findings, and assessment of real-world performance and adaptability of agricultural practices.
Water Source	Precisely controlled irrigation, ensuring optimal moisture levels.	Primarily rainfed, with supplemental irrigation where water resources are available and economically feasible.
Scale	Small-scale, intensive; allows for detailed, frequent measurements on individual plants or small soil volumes.	Larger-scale, extensive; evaluates interventions across broader areas, reflecting typical farm management units.
Challenges	May not fully represent complex field interactions; results may not be directly transferable without field validation	High environmental variability; difficulty in controlling all factors; results can be site-specific and influenced by unforeseen events.

Collectively, these publications weave a comprehensive narrative on the stewardship of Sandy Arenosols, Luvisols, Chernozem and Inseptisoil, highlighting the importance of tailored management strategies, the adoption of sustainable practices, and the role of policy in safeguarding soil health.

Through the integration of scientific research, technological innovation, and supportive policy measures, agriculture can navigate the challenges posed by these diverse soil types, ensuring productivity and sustainability for future generations.

2.3.2 Management Practices

Effective cover crop management is essential for maximizing their benefits. Managing mixtures requires more knowledge and understanding of the growth habits, seeding rates, and termination methods for multiple species (Liebman & Schulte, 2015). Despite their advantages, cover crop mixtures can also present challenges:

- Complexity in Management: Managing mixtures requires more knowledge and understanding of the growth habits, seeding rates, and termination methods for multiple species. This complexity can be daunting, especially for farmers new to cover cropping (Williams A et al., 2018).
- Cost and Availability: Obtaining seeds for a diverse mix and the cost associated with it can be higher than for single species cover crops. Additionally, customizing seed mixes to suit specific farm needs may not always be straightforward (Schipanski et al., 2014).
- Competition among Species: There is a possibility that in a mixture, one species could dominate, suppressing the growth of others and reducing the overall benefits. This requires careful selection of species that complement rather than compete with each other (Bowles et al., 2020).

While cover crop mixtures offer enhanced benefits over single-species plantings, they come with increased management complexity and potential challenges. The success of these mixtures depends on careful planning, selection of species based on farm goals, and adaptive management practices. Additionally, (Dumas et al., 2022) highlight that policy incentives for cover crop adoption need to account for regional variations in implementation costs and benefits, suggesting that targeted subsidies based on quantified ecosystem service delivery could increase adoption rates by up to 300% compared to flat-rate payment schemes.

Nonetheless, when managed well, cover crop mixtures can significantly contribute to the resilience and productivity of agricultural systems, promoting soil health, biodiversity, and ecosystem services. The timing of cover crop planting and termination is also crucial. For instance, a winter cover crop mix like winter rye and hairy vetch would be planted in the fall after harvesting the main crop to provide overwinter soil protection and nitrogen for spring planting. Summer mixes, like sorghum-sudangrass and cowpeas, might be used in warmer regions or during fallow periods in temperate zones to improve soil health and suppress pests and diseases (Clark, 2007). Seeding rates need to be adjusted based on the specific cover crop species or mixture, with higher rates generally recommended for weed suppression and lower rates for maximizing biomass production (SAREP, 2017).

Termination methods, such as mowing, rolling, or using herbicides, should be chosen based on the cover crop species, the subsequent crop, and the overall management goals. For example, mowing or rolling can be effective for terminating cover crops before no-till planting, while herbicides may be necessary for certain species or in situations where rapid termination is required (Mirsky et al., 2011). The most common examples of effective cover crop mixtures: 1. Winter Rye + Hairy Vetch: This mix is popular for its soil protection and nitrogen-fixing capabilities. Winter rye provides quick ground cover to prevent erosion and suppress weeds, while hairy vetch fixes nitrogen in the soil for the next crop (Clark, 2007). 2. Oats + Radishes + Peas: This combination is used for quick ground cover, nitrogen fixing, and soil compaction alleviation. Radishes create channels in compacted soil, improving water infiltration, while oats and peas provide biomass and fix nitrogen, respectively (Schipanski et al., 2014). 3. Sorghum-Sudangrass + Cowpeas + Buckwheat: Ideal for summer cover, this mix suppresses weeds, fixes nitrogen (cowpeas), and attracts beneficial insects (buckwheat), with sorghum-sudangrass adding substantial biomass for soil health (Bowles et al., 2020). The timing for using mixed cover crops largely depends on the crop rotation and the specific goals of the cover crop. For example, a winter cover crop mix like winter rye and hairy vetch would be planted in the fall after harvesting the main crop to provide overwinter soil protection and nitrogen for spring planting. Summer mixes, like sorghum-sudangrass and cowpeas, might be used in warmer regions or during fallow periods in temperate zones to improve soil health and suppress pests and diseases.

2.3.3 Improvement of Soil-Microbial Status and the Importance of Soil Health Parameters

Cover crops have a profound impact on the soil microbial community, enhancing both its diversity and activity. cover crops contribute to increased soil microbial activity through the addition of organic matter and the provision of root exudates that serve as a food source for microorganisms. This enhanced microbial activity is crucial for nutrient cycling, organic matter decomposition, and overall soil health. The use of cover crop mixtures can be particularly beneficial as it provides a diversity of root exudates and organic matter inputs, supporting a wider range of microorganisms (Larkin, 2024). According to (Giusti et al., 2023) and a meta-analysis by (Marcillo & Miguez, 2017), agricultural soils harbor approximately 10^9 microbial cells per gram. Furthermore, these studies indicate that cover cropping systems typically support significantly greater microbial diversity—in some cases 30-45% more—than conventional systems, leading to enhanced ecosystem functions including nutrient cycling and disease suppression. The importance of soil microbial communities for nutrient cycling, disease suppression, and overall soil health is well-established (Rinaudo et al., 2010; Biró et al., 2005c). For instance, mycorrhizal fungi, which are often enhanced by cover crops, play a critical role in phosphorus uptake and plant growth, while certain bacteria can suppress soilborne pathogens (Smith & Read, 2008; Larkin & Griffin, 2007).

Soil health is a critical issue of sustainable agriculture, influencing plant growth, ecosystem function, and climate regulation. Various parameters, including pH, electrical conductivity (EC), labile carbon, nitrate (NO_3), ammonium (NH_4), fluorescein diacetate (FDA) hydrolysis, and mycorrhizal colonization percentage, provide insights into the soil's biological, chemical, and physical state. Understanding these parameters helps in making informed management decisions to enhance soil quality and agricultural productivity. pH: Soil pH is a fundamental parameter that affects nutrient availability, microbial activity, and plant growth. Most nutrients are readily available to plants in slightly acidic to neutral soils (pH 6.0–7.0). Extremes in pH can lead to nutrient lock-up, affecting plant health and yield (Brady & Weil, 2008). Adjusting soil pH through amendments can optimize nutrient availability and enhance crop performance.

Electrical Conductivity (EC): EC measures soil salinity, indicating the concentration of soluble salts. High EC levels can hinder plant water uptake, leading to osmotic stress and reduced growth. Monitoring EC is essential for managing irrigation practices and salt accumulation, particularly in arid and semi-arid regions (Rhoades et al., 1999). NO_3 and NH_4 are primary forms of nitrogen available to plants. Their concentrations reflect the soil's nitrogen-supplying capacity. Balanced nitrogen levels are vital for plant growth, but excess nitrogen can lead to nutrient leaching and environmental pollution. Therefore, managing nitrogen inputs is key to sustainable crop production (Di & Cameron, 2002). Fluorescein Diacetate (FDA) Hydrolysis: FDA hydrolysis is an indicator of overall microbial activity in soil. Since microbes play a pivotal role in organic matter decomposition and nutrient cycling, high FDA activity suggests a vibrant microbial community and healthy soil. This parameter is used to assess the impact of agricultural practices on soil life (Schnürer & Rosswall, 1982; Sánchez et al., 2008; Biró et al., 2012).

Labile Carbon: Labile carbon, the easily decomposable fraction of soil organic matter, is crucial for maintaining soil structure, fertility, and microbial activity. It serves as a primary energy source for soil microorganisms, driving nutrient cycling and soil aggregation processes. High levels of labile carbon are indicative of healthy, productive soils (Gregorich et al., 2003). High levels of labile carbon indicate a soil rich in organic matter with a robust microbial community, leading to improved plant growth and yield. Moreover, soils with high labile carbon can sequester more carbon, mitigating climate change by removing CO_2 from the atmosphere. Practices that increase labile carbon in soil include the incorporation of cover crops, organic amendments (such as compost or manure), and reduced tillage. These practices not only boost labile carbon but also contribute to overall soil health by enhancing biodiversity, improving water-holding capacity, and reducing erosion (Cotrufo et al., 2013). Measurement of labile carbon can serve as an early indicator of changes in soil health, providing valuable feedback on the effectiveness of land management practices. Enhancing labile carbon levels is a key strategy in sustainable agriculture, aiming to maintain productive soils that support healthy crops and ecosystems (Six et al.,2002).

Mycorrhiza %: Mycorrhizal fungi form symbiotic relationships with plant roots, enhancing water and nutrient uptake, particularly phosphorus. The percentage of root colonization by mycorrhizae reflects the extent of this beneficial association. High mycorrhizal colonization can improve plant stress tolerance, nutrient acquisition, and soil structure (Smith & Read, 2008). Arbuscular mycorrhizal fungi (AMF) are pivotal in advancing sustainable agricultural practices (Biró et al.,2005b). These fungi form a symbiotic association with the roots of most terrestrial plants, facilitating enhanced access to water and essential nutrients, notably phosphorus and nitrogen elements crucial for plant growth but often limited in availability due to soil mineralization rates and leaching losses. By extending the root system through vast networks of hyphae, AMF can access nutrients far beyond the plant's root zone, while receiving carbohydrates produced by the plant through photosynthesis. This mutualistic relationship not only boosts plant growth and health but also significantly improves soil structure and fertility (Smith and Read, 2008; Parniske, 2008). AMF plays a critical role in aggregating soil particles, thereby enhancing soil porosity and aeration. The symbiosis between plants and AMF is also a key player in carbon sequestration within soil systems. The hyphae of these fungi are significant conduits for the transfer of carbon from plants to the soil, contributing to soil organic matter formation and stabilization. This increased soil structure stability contributes to better water retention and reduced erosion, vital for maintaining productive soils (Rillig and Mummey, 2006; Wilson et al., 2009). Moreover, AMF has been shown to improve plant water-use efficiency and drought resistance, crucial under the current challenges of climate change (Auge, 2001; Ruiz-Lozano, 2003). The introduction of cover crops into agricultural systems influences AMF populations positively. Cover crops can support a diverse community of AMF by providing continuous root habitats and organic matter. Cover crops not only provide a continuous food source for AMF during periods when main crops are not grown, but they also contribute to the diversity and abundance of AMF in the soil. This increased microbial biodiversity can lead to more resilient soil systems, capable of supporting high-yielding crops while maintaining or improving soil health over time (Verbruggen and Kiers, 2010; Bowles et al., 2017). Recent studies underscore the significance of integrating cover crops with AMF to bolster soil health and fertility, facilitating more efficient nutrient cycling and higher crop yields. Practices such as reduced tillage, organic fertilization, and diverse crop rotations further enrich AMF diversity and function, contributing to the resilience and sustainability of agro-ecosystems (Dudás et al., 2017; Zhang et al., 2016; Shen et al., 2023; Biró et al., 2005a).

3. MATERIALS AND METHODS

3.1 Experimental Design

The experimental design employed in this study aligns with standardized protocols proposed by (Hargreaves et al., 2023; Krupek et al., 2022), who emphasize the importance of consistent methodology across diverse agroecosystems to enable meaningful comparisons of cover crop effects on soil health parameters.

3.1.1 Pot Experiment

Location and Soil Characteristics:

The pot experiment was conducted under controlled greenhouse conditions at the Faculty of Agricultural and Environmental Sciences, MATE University, Buda Campus, Budapest, Hungary. The substrate used was sandy soil (Arenosols) with a neutral pH of 7.4 (Table 2). Soil classified as sandy texture was collected from the Soroksár Botanical Garden (47.4019 N, 19.1551 E). This soil was selected for its commonality in agricultural settings and its relevance to the cover crops chosen for this study. Its physical and chemical properties, particularly its texture and pH, were expected to interact with the root systems and exudates of the cover crops, potentially influencing the overall soil health and the crops' growth performance.

Plant Materials and Experimental Setup:

To evaluate the effects of different cover crop species on soil properties and subsequent main crop performance. The pot experiment was conducted utilizing five different cover crop species, chosen for their diverse traits and potential benefits to soil quality. These species included *Vicia faba* (broad bean), *Phacelia tanacetifolia* (phacelia), *Avena strigosa* (black oat), *Brassica carinata* (Ethiopian mustard), and *Vicia benghalensis* (purple vetch). These species were chosen for their diverse traits and potential benefits to soil quality, specifically their roles in single or double symbiosis. Broad bean and purple vetch were selected for their ability to form double symbiosis (with rhizobia for nitrogen fixation and mycorrhizal fungi for phosphorus uptake). Phacelia and black oat were chosen as single symbiosis species (mycorrhizal fungi only), while Ethiopian mustard represented a non-symbiotic plant. Additionally, a mixed crop treatment incorporating all five species and a control with non-planted pots were included to ascertain the individual and combined effects of these crops on soil properties. The cover crops were grown in standard plastic pots, each with a volume capacity of 2000 grams.

Each pot was sown with ten individual plants of a single cover crop species, ensuring uniformity in plant density across treatments. For the mixed crop pots, a total of fifteen plants were used, comprising three plants from each of the five cover crop species, to maintain proportional representation.

Figure 1 Starting Pot experiment (Kabalan, 2020)

Growth Conditions and Maintenance:

The greenhouse environment was regulated to simulate optimal growing conditions for the cover crops. The temperature was maintained at an average of 19°C during the daytime and 10°C at night to reflect common seasonal variations. Humidity was controlled at 52%, which is within the favorable range for the growth of these crops. The experimental period spanned eight weeks; a duration selected based on the typical growth cycle of the cover crops to maturity. Throughout this period, plants were watered and maintained under these controlled conditions to minimize external variability and stress factors.

Experimental Timeline (2020 and 2021):

The pot experiment was conducted for a three-month period, from October 2020 to January 2021. The following timeline and practices were observed. The seeding period was in October 2020, and the Harvesting happened in January 2021. The cover crop biomass (both shoot and root) was harvested, and after measuring the dry biomass, it was returned to the soil and thoroughly mixed in as green manure. Each treatment was replicated 4 times to ensure statistical robustness.

Table 2. Overview of Pot Experiment Treatments and Conditions

Treatment Code	Cover Crop Species	Planting Density (plants/pot)	Soil Type	Soil pH	Treatment Type
T1	*Vicia faba* (Broad bean)	10	Arenosol	7.4	Single species
T2	*Phacelia tanacetifolia* (Phacelia)	10	Arenosol	7.4	Single species
T3	*Avena strigosa* (Black oat)	10	Arenosol	7.4	Single species
T4	*Brassica carinata* (Ethiopian mustard)	10	Arenosol	7.4	Single species
T5	*Vicia benghalensis* (Purple vetch)	10	Arenosol	7.4	Single species
T6	MIX (All five species combined)	15 (3 per species)	Arenosol	7.4	Mixed species
T7	No plants (control)	0	Arenosol	7.4	Control (bare soil)

Figure 2 pot experiment (Kabalan, 2020)

3.1.2 Field Experiment with CC

Site Description and Soil Characteristics:

The field experiment was conducted on an agricultural site of the Tishreen university in Latakia city, Syria (35.5167° N, 35.7833° E). The experimental layout followed a Randomized Complete Block Design (RCBD) with 4 blocks, as illustrated in (Figure 3). Each plot measured 2x2 meters, resulting in a total plot size of 4 m^2. The seeding rate for each cover crop species was approximately 50-100 seeds per designated plot, ensuring even distribution and emulating natural planting conditions. The plant density for each species was thus approximately 12.5-25 plants/m^2. The site is characterized by a Mediterranean climate with mild, wet winters and hot, humid summers. The field site featured inceptisol soil that had not been previously planted (Table 3,4). Inceptisols are known for their minimal horizon development and are often found in areas with a young geological age, such as alluvial plains, which make them suitable for examining the initial impacts of cover crops on soil properties. Prior to its use for the experiment, this uncultivated portion of the university land was characterized by the presence of wild grass. Therefore, the type of land use system for this specific territory before the experiment could be described as uncultivated university land with natural vegetation (wild grasses), distinguishing it from other parts of the university land that might have been under cultivation. Inceptisols are moderately fertile and often contain clay loam textures with good drainage, making them suitable for both field and horticultural crops. The inceptisols in Latakia are typically formed over limestone or alluvial deposits and have relatively good water-holding capacity but low organic matter due to erosion and historical underuse.

The site's soil exhibited a variable pH range from 6.8 to 7.9 across different samples, indicating slight acidity to neutral conditions. Such a pH spectrum is conducive to a wide variety of agricultural crops and mirrors the soil conditions of the greenhouse experiment conducted in Hungary, providing a comparative basis between field and controlled environments. The field site featured inceptisol soil that had not been previously planted Table 4.

Table 3. Agrotechnical Operation of The Syrian Field Experiment

Operation	Timing	Description
Soil Preparation	March 5, 2023	Manual tillage with hoe and rake to a depth of 15 cm
Seeding	March 7, 2023	Hand seeding with filling the block with species per 2×2 m plot
Irrigation	Weekly	Supplementary hand watering (5–7 L/plot/week) as needed
Weed Control	Biweekly	Manual removal to prevent competition
Cover Crop Termination	May 15, 2023	Hand cutting and biomass removal
Main Crop Planting	May 18, 2023	Manual planting of maize seeds in all plots

Table 4. Soil Properties of the Field Experiment Site (Latakia, Syria)

Soil Property	Measured/Typical Value	Remarks
Soil Type	Inceptisol	Young soil with limited profile development
Texture	Silty clay loam	Good water-holding capacity
pH	6.8 – 7.9	Slightly acidic to neutral
Soil Organic Matter (SOM)	1.3% – 1.9%	Low to moderate organic content
Available Phosphorus (P)	12 – 16.2 mg/kg	Moderately low; depends on management history
Available Potassium (K)	90 – 150 mg/kg	Medium to high
Iron (Fe)	3.0 – 6.0 mg/kg	Adequate levels
Zinc (Zn)	1.1 – 2.6 mg/kg	May require supplementation in sensitive crops
Manganese (Mn)	3.0 – 6.1 mg/kg	Generally sufficient
Copper (Cu)	0.4 – 1.4 mg/kg	Acceptable levels for most crops

Environmental Conditions and Cover Crop Selection:

The field experiment mirrored the cover crop selection of the greenhouse study, incorporating five different cover crops: *Trifolium* spp. (clover), *Lens culinaris* (lentil), *Brassica napus* (rapeseed), *Raphanus sativus* (radish), and *Secale cereale* (rye), along with a mixed treatment comprising all five species and control plots without any plant cover. The environmental conditions during the experiment were typical of a Mediterranean climate. Latakia generally experiences warm, muggy, dry, and clear summers, and cool, wet, windy, and partly cloudy winters. During the cover crop growing season (March to May), Latakia transitions from its cool, wetter period into the clearer, drier part of the year. Daytime temperatures ranged from 18°C to 23°C, while nighttime temperatures dropped to a cooler 12°C to 15°C. These fluctuations are reflective of the diurnal temperature variations that can impact plant growth and soil processes. The humidity levels were maintained around 60-65%, providing a moderately moist environment for crop development. The total rainfall was approximately 150-180mm and the sunshine hours between 6 – 8 hours/day.

Experimental Operations and Timeline:

The experiment was scheduled for a duration of 10 weeks to allow the cover crops to pass through most of their growth cycle and reach maturity, at which point they were harvested. The field experiment involved specific agrotechnical operations and a defined timeline to assess the performance of cover crops under Syrian field conditions. Distributing approximately five seeds at each designated plot within the field to ensure even crop distribution and to emulate natural planting conditions executed seeding. The experiment was scheduled for a duration of 10 weeks to allow the cover crops to pass through most of their growth cycle and reach maturity, at which point they were harvested.

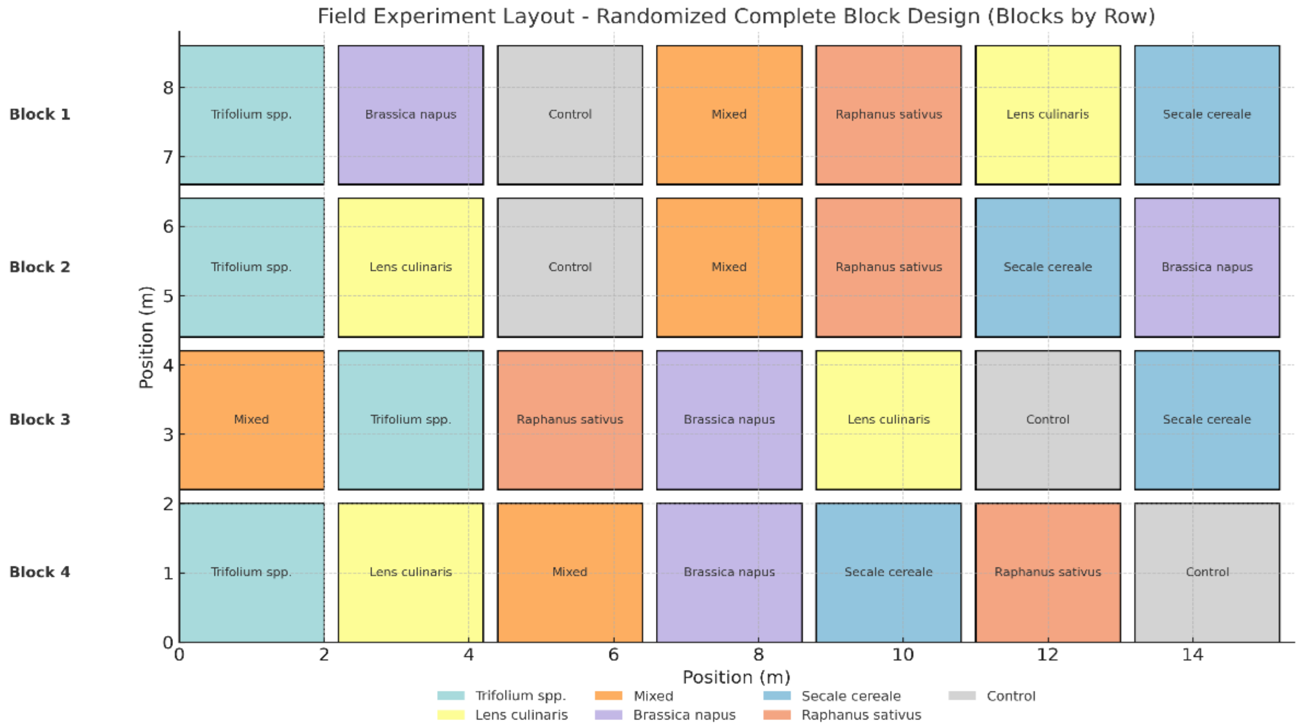

Figure 3 Field experiment layout and plot arrangement.

Figure 4 Field experiment Tishreen University Syria (Kabalan, 2022)

3.2 Examination of soil characteristics

3.2.1 Soil Types, Characteristics and Sampling

Three soil types were selected for this study Arenosols, Chernozems, and Luvisols. Each soil type exhibits unique physico-chemical properties, as described in Table 5**.**

Arenosols are characterized by their sandy texture, low organic matter content, and high bulk density. They are commonly found in arid and semi-arid regions and are known for their low water-holding capacity. The Arenosols were collected from the Soroksár Botanical Garden (47.4019°N, 19.1551°E).

Chernozems are characterized by their loamy texture, high organic matter content, and relatively high bulk density. They are considered highly fertile soils, ideal for growing a wide range of crops. The Chernozems were collected from Kömlőd (Komárom-Esztergom County). Luvisols are characterized by their clay-loam texture, moderate organic matter content, and high bulk density. They are known for their high water-holding capacity and are often found in temperate regions. The Luvisols were collected from Baranya County, specifically from the area of Zöldvárosi Élményfarm alapítvány (47°23′44″N, 19°08′43″E).

Table 5. Physico-chemical characteristics of three soil types used in the experiment.

Soil type by WRB	Texture	pH	SOM (%)	Bulk density (g/cm)	Water holding capacity (%)	Origin
Arenosols	Sand	7.46	1.16	1.65	15	Soroksár Botanical Garden
Chernozems	Loam	7.35	2.81	1.35	40	Kömlőd (Komárom-Esztergom County)
Luvisols	Clay loam	4.91	1.64	1.25	50	Baranya County

Soil properties were assessed systematically throughout both experimental phases (under cover crops and after their incorporation during main crop cultivation). The measurements aimed to evaluate the impact of cover crop treatments on soil biological activity, nutrient availability, and general soil health. The experiment was conducted in the Mate Buda campus greenhouse (MATE University, Hungary: 47.4979°N, 19.0402°E). The experimental timeline was as follows: Season 1: March 2022 - August 2022, and Season 2: March 2023 - August 2023. Table 6 shows the soil parameters and timelines applied in the experiment.

Table 6. Soil parameter analysis timeline and sampling design.

Parameters	Methodology	Sampling Timing	Crop Phase	Sample Type
FDA (microbial activity)	FDA hydrolysis assay	After 8–10 weeks	Under CC	Soil
FDA (residual activity)	FDA hydrolysis assay	2.5 months post main crop	Under Main Crop	Soil
EC	AD 8000 Bench Meter	At CC maturity	Under CC	Soil solution
EC	AD 8000 Bench Meter	At crop harvest	Under Main Crop	Soil solution
NO_3^-	Spectrophotometric (410 nm)	After CC, after crop	Both	Soil extract
NH_4^+	Spectrophotometric (655 nm)	After CC, after crop	Both	Soil extract
N_{min}	Calculated (NO_3^- + NH_4^+)	After CC, after crop	Both	Soil
POXC	$KMnO_4$ oxidation	After CC phase only	Under CC	Soil
AMF Colonization (MYCO%)	Root staining and microscopic quantification	After CC and after crop	Both	Root samples

3.2.2 Biological Properties Analysis

Fluorescein Diacetate (FDA) Hydrolysis Assay:

Our research utilized the Fluorescein Diacetate (FDA) Hydrolysis Assay to gauge potential microbial activity within soil samples that had been enriched with various organic amendments for the 2 phases. This technique, as outlined by (Green, Stott, & Diack 2006) and further refined by (Villányi et al. 2006), is renowned for its effectiveness in providing insights into the enzymatic functions of soil microorganisms.

To conduct the assay, soil samples were carefully collected from each experimental pot. For each sample, 1 gram of soil was placed into a test tube, to which 7.5 ml of 60 mM phosphate buffer was added to achieve suspension. This was followed by the addition of 100 µl of FDA stock solution (2 mg/mL). The mixture was then vortexed for uniformity, shaken manually, and incubated at 30°C for 3 hours in a shaker incubator set at 200 rpm. Post-incubation, 7.5 ml of acetone was added to halt the reaction. This mixture was then shaken once more and filtered into a clean falcon tube for analysis. Fluorescence intensity, indicating microbial activity, was measured using a spectrophotometer at a wavelength of 490 nm, including controls for comparison.

Mycorrhizal Colonization Assessment:

In our comprehensive analysis, we conducted an extensive colonization assay to evaluate the presence and extent of arbuscular mycorrhiza fungi (AMF) colonization within the root systems of various plants. This assessment covered single and mixed cover crops, as well as the primary agricultural crops of interest, corn and pepper. The aim was to quantify the colonization frequency by AMF (denoted as MYCO%) across all plant types, providing insights into the symbiotic relationships between these fungi and plant roots. The methodology for determining AMF colonization was adapted from the pioneering work by (Phillips & Hayman 1970), with modifications to suit our specific research needs. The process began with the meticulous washing of plant roots using tap water to remove soil and debris. Subsequently, the roots underwent a softening process in a 7% potassium hydroxide (KOH) solution for 24 hours, ensuring that the tissue became pliable enough for further processing. After softening, the roots were rinsed thoroughly in water to remove any remaining KOH.To prepare the roots for staining, they were acidified by soaking in 5% lactic acid, a step that could last anywhere from 1 to 24 hours depending on the root tissue characteristics. This acidification process was crucial for the successful uptake of the stain. Staining was then conducted using a 0.01% aniline blue solution in 5% lactic acid, where the roots remained submerged for 24 hours at room temperature. This specific staining procedure highlights the presence of AMF within the root tissues, making them visible under microscopic examination. After staining, the roots were preserved in lactoglycerol, a storage medium that prevents deterioration and maintains the integrity of the stained samples until they were prepared for microscopic evaluation. For the quantification of AMF colonization, thirty 1-cm root fragments were sampled from each plant. These fragments were then mounted on slides and examined microscopically to assess the frequency and extent of mycorrhizal colonization. The colonization parameters were quantified as MYCO%, representing the percentage of root length colonized by AMF.

This detailed approach to measuring mycorrhizal colonization not only provided valuable data on the symbiotic interactions between plants and AMF but also contributed to a deeper understanding of the potential benefits of these relationships. By examining a wide array of cover crops and main crops, our study offers insights into how AMF colonization varies across different plant species and agricultural practices, informing strategies to enhance plant health and soil fertility through the promotion of beneficial fungal associations.

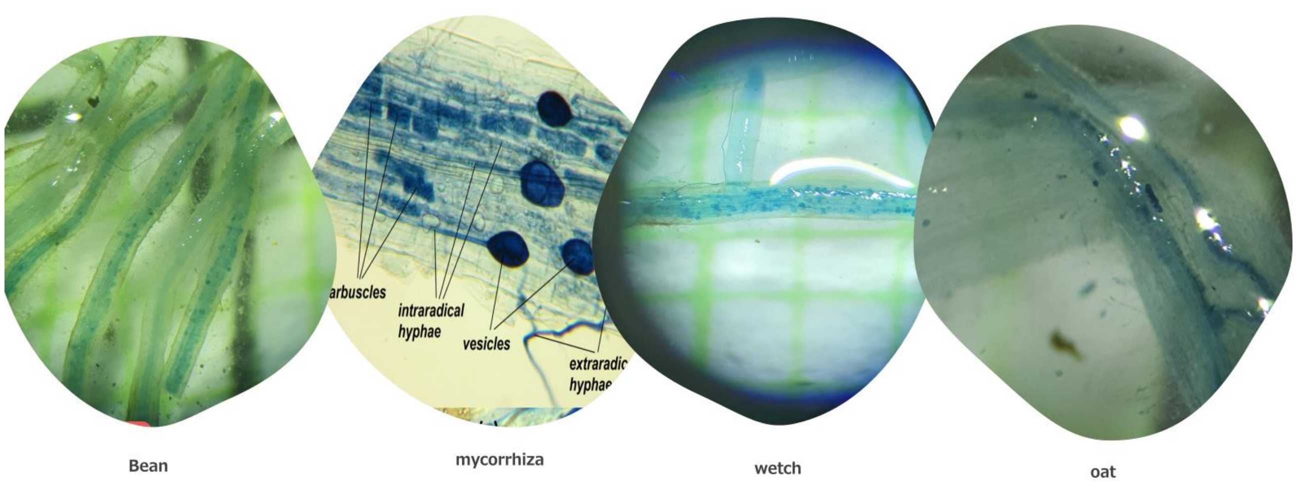

Figure 5 Active Mycorrhiza (Sylvia et al., 2005; Kabalan 2022)

Permanganate Oxidizable Carbon (POXC) Analysis:

The Permanganate Oxidizable Carbon (POXC) assay was employed to quantify the labile carbon fraction within the soil, which is readily oxidizable by potassium permanganate, reflecting the dynamic component of soil organic matter that is most sensitive to management changes (Calderón et al., 2017). This measurement serves as a critical indicator of soil health and fertility, given that labile carbon is pivotal for soil microbial activity and nutrient cycling.

Procedure for Determining Permanganate Oxidizable Carbon (POXC)

1. Sample Collection and Preparation: Soil samples were systematically collected from each experimental pot. Following collection, the samples were air-dried at ambient room temperature to standardize moisture content and facilitate homogenous reaction conditions during the assay.
2. Modification of the Standard Method: The assay was conducted in accordance with the methodology outlined by (Weil et al., 2003), with a specific modification in the concentration of the potassium permanganate (KMnO4) solution used. The adapted procedure utilizes a 0.02 M KMnO4 solution, which is critical for accurately estimating the oxidizable carbon content by this reagent.
3. Assay Execution: For the assay, 1 gram of the air-dried soil was vigorously shaken with 10 mL of the 0.02 M KMnO4 solution for a duration of 5 minutes. This shaking process facilitates the oxidation of labile carbon by the KMnO4. Subsequently, the mixture was subjected to centrifugation to separate the solid and liquid phases. This step ensures that the supernatant, containing the oxidized carbon in solution, can be accurately analyzed.
4. Preparation for Spectrophotometric Analysis: A volume of 0.2 mL of the clear supernatant was then carefully transferred into a 15 mL tube. To this, 10 mL of deionized water was added to dilute the solution, preparing it for absorbance measurement.
5. Absorbance Measurement: The diluted sample's absorbance was measured at a wavelength of 565 nm using a Biochrom Libra S22 spectrophotometer. The selection of this specific wavelength is due to its sensitivity to the changes in concentration of the permanganate ion in solution, reflecting the amount of carbon that has been oxidized.

3.2.3 Soil Chemical Parameters

Soil Electrical Conductivity (EC) Measurement:

In our study, the electrical conductivity (EC) of soils was evaluated across various cover crops and their mixtures within a controlled pot experiment. This analysis also extended to a non-planted control soil to establish a baseline comparison. The objective was to measure the EC in both the initial soil mixtures under different cover crops and, subsequently, in soils associated with the primary crops of corn and pepper during the second phase of the experiment. To achieve this, we employed an electrical conductivity meter (specifically, the AD 8000 pH/MV/EC/TDS & T 0 Bench Meter from Romania) for the measurements. This instrument facilitated the accurate determination of EC in soil solutions. Each cover crop variant, including the control group and the main plant of pepper and corn, was subjected to four replicates of EC measurement to ensure reliability and statistical robustness of the data. Electrical conductivity of soils is a critical parameter as it offers insights into the concentration of soluble nutrients available. These soluble salts directly influence plant growth by affecting nutrient uptake. By measuring EC, we aimed to quantify the nutrient content in soils under different cover crops and their impact on the subsequent cultivation of main crops like corn and pepper. This approach allows for a nuanced understanding of how cover crops might enhance or influence the nutrient dynamics within soil, ultimately informing sustainable agricultural practices.

Nitrate (NO_3) and Ammonium (NH_4) Content Measurement:

The determination of NO_3 concentration in soil extracts involves a multi-step chemical process that begins with the preparation of the soil sample. The initial step requires extracting NO_3 from the soil, typically achieved by agitating a known quantity of soil with a specific volume of water, followed by filtration to obtain a clear extract (Monteiro et al., 2003).

1. Preparation of Soil Extract: For this analysis, a 5 ml volume of the filtered soil extract is used. This extract represents the soluble fraction of the soil where NO_3 is dissolved, alongside other soluble minerals and organic compounds.

2. Chemical Reaction Initiation: To the soil extract, 1 ml of sodium salicylate ($C_7H_5NaO_3$) is added. Sodium salicylate reacts with NO_3 ions in the presence of sulfuric acid to form a complex that can be quantified spectrophotometrically. The mixture is then evaporated to dryness, which concentrates the sample and facilitates the formation of a precipitate, indicating the presence of reactive components for the subsequent steps.
3. Dissolving the Precipitate: The formed precipitate is dissolved in 1 ml of concentrated sulfuric acid (H_2SO_4). This step is crucial as it ensures that all the reactive components are fully dissolved and available for the next stage of the reaction. Sulfuric acid breaks down complex molecules and assists in the release of NO_3 ions from the precipitate.
4. Neutralization and Dilution: The acidic solution is then carefully neutralized by adding it to a beaker containing 25 ml of distilled water. Subsequently, a 5 ml of 10 M sodium hydroxide (NaOH) solution is introduced to neutralize the acid. This step is essential for maintaining the integrity of the NO_3 ions and preparing the solution for accurate spectrophotometric analysis. The volume of the mixture is adjusted to 50 ml with distilled water to standardize the solution for measurement.
5. Spectrophotometric Measurement: The final analytical step involves measuring the NO_3 concentration using a spectrophotometer, set at a wavelength of 410 nm. This wavelength is specifically chosen for its ability to detect the color change associated with the NO_3 ion presence in the solution. The intensity of the color change directly correlates with the NO_3 concentration, providing a quantitative measure of NO_3 levels in the soil extract.

To assess the (NH_4^+) concentration in soil samples, a detailed procedure was developed, emphasizing the chemical reactions and spectrophotometric analysis involved. This method facilitates the accurate quantification of NH_4, a critical nutrient affecting plant growth and soil fertility. The determination of NH_4 concentration is crucial for understanding nitrogen availability in soils, as NH_4 is a key form of nitrogen uptake by plants. The following steps outline the method used to quantify NH_4 levels:

1. Preparation of Soil Suspension: A soil suspension is prepared by mixing soil with 0.1 M calcium chloride ($CaCl_2$) solution in a 1:5 ratio. Calcium chloride acts as an extracting agent, pulling NH_4 ions from the soil particles into the solution. The mixture is shaken vigorously for 60 minutes to ensure thorough mixing and extraction of NH_4 ions into the liquid phase. After shaking, the suspension is allowed to settle, facilitating the separation of the solid and liquid phases.

2. Filtration: The settled suspension is then filtered to obtain a clear liquid phase, which contains the extracted NH_4 ions. This step is essential to ensure that the subsequent chemical reactions and measurements are not hindered by solid particles.
3. Chemical Reaction for NH_4 Detection: To 10 ml of the filtered soil extract, 1 ml of oxidizing reagent is added. This reagent is a mixture of sodium hydroxide (NaOH) and dichlorocyanuric acid sodium salt, which reacts with NH_4 ions to form a measurable complex. Additionally, 1 ml of salicylate reagent is introduced to the mixture. This reagent consists of sodium salicylate, tri-sodium citrate, and sodium nitroprusside, enhancing the color development for spectrophotometric analysis. The combination of these reagents with the NH_4 ions initiates a colorimetric reaction, resulting in a colored compound proportional to the NH_4 concentration.
4. Spectrophotometric Measurement: The resulting solution, now containing the colored compound indicative of NH_4 concentration, is analyzed using a spectrophotometer. The spectrophotometer is set to a wavelength of 655 nm; a specific wavelength chosen for its sensitivity to the color change associated with the presence of NH_4 ions in the solution. The intensity of the color, measured by the spectrophotometer, directly correlates with the NH_4 concentration in the soil extract, allowing for a precise quantification of NH_4 levels.

Subsequently, the total mineral nitrogen (N_{min}) was calculated by aggregating the concentrations of both NO_3 and NH_4 nitrogen present in the samples.

3.3 Determination of CC biomass and main crop characteristics

The experiment was conducted as a controlled pot experiment within the Mate Buda campus greenhouse (MATE University, Hungary: 47.4979°N, 19.0402°E). This setup allowed for precise control over environmental conditions and experimental variables. We investigated the growth and development of cover crops and main plants over. The experimental timeline was structured across two seasons: Season 1: March 2022 - August 2022

- Cover Crop Phase: Cover crops were planted in March 2022. The experimental period for cover crop growth spanned eight weeks, a duration selected based on the typical growth cycle of the cover crops to maturity. Cover crops were terminated in May 2022.
- Main Crop Phase: Following the termination and incorporation of cover crops, main crops (corn and green pepper) were planted in May 2022. These main crops were harvested approximately two and a half months after planting, in August 2022.

Season 2: March 2023 - August 2023

- The experimental cycle was repeated in Season 2, mirroring the timeline and procedures of Season 1 to validate the sustainability and repeatability of the experimental outcomes.

Plants were carefully Harvested. After harvesting, we assessed biomass production by considering both fresh and dry weights of roots and shoot biomass content, Above-ground biomass (fresh and dry weight), root biomass (fresh and dry weight). Additionally, the cover crop biomass was blended with the soil as green manure during the second phase of the experiment. Dry biomass measurements were taken, and the samples were dried in an oven at 70°C for 48 hours to obtain accurate results. These findings contribute valuable insights to sustainable agriculture practices. Following this incorporation: Corn (*Zea mays* L., Decalb DKC3972) was planted in the pots of the CC, with 3 seeds per pot, across all treatments and soil types. This planting strategy was designed to assess the influence of the preceding cover crop management practices on the growth dynamics and yield potential of corn. Two distinct cover crop mixtures, MIX1 and MIX2, were utilized in this study:

MIX1 comprised Italian ryegrass (*Lolium multiflorum*), purple vetch (*Vicia benghalensis*), and peas (*Pisum sativum*). MIX2 was a combination of three single cover crops: mustard (*Brassica carinata*) broad bean (*Vicia faba*), and black oat (*Avena strigose*).

Green pepper (*Capsicum annuum L.*) seeds were sown in the designated pots for control, MIX1, and MIX2 treatments within sandy and Chernozem soils. This selection aimed to explore the effects of the preceding cover crop phase and soil amendments on the growth and yield of these primary crops. Approximately two and a half months after planting, both the corn and green pepper plants were harvested. This period allowed sufficient time for the crops to grow under the influenced soil conditions, offering a window to gauge the cover crops' impact on the primary crops' growth, health, and productivity. The harvesting process marked the culmination of the secondary crop phase, providing critical data for analysis on the effectiveness of cover crops in sustainable agriculture practices. This structured experiment was repeated over the course of two years, with the initial year dedicated to the establishment and assessment of cover crops (including MIX1, MIX2, and control treatments) followed by the planting of main crops under consistent conditions within the same pots. The subsequent year mirrored this cycle to validate the sustainability and repeatability of the experimental outcomes. After harvesting, we assessed biomass production by considering both fresh and dry weights of roots and shoot biomass content (Above-ground biomass (fresh and dry weight), root biomass (fresh and dry weight)). Additionally, the cover crop biomass was blended with the soil as green manure during the second phase of the experiment. Dry biomass measurements were taken, and the samples were dried in an oven at 70°C for 48 hours to obtain accurate results. These findings contribute valuable insights to sustainable agriculture practices.

Figure 6 Main crops planting (Corn & Pepper) (Kabalan et al., 2022)

3.4 Statistical evaluations

Statistical analyses were conducted using R software, version 4.2.1. The impact of different treatments on the measured variables was analyzed employing a General Linear Model (GLM). The effectiveness of treatments was determined using Wilk's lambda, a measure of the multivariate significance of group differences. In instances of significant outcomes from the overall test, post hoc comparisons were performed using the Bonferroni correction method to control for type I error across multiple tests, thereby assessing the univariate main effects with greater precision.

Effect sizes and the power of observed effects were quantified using the partial eta squared (η^2) statistic, which offers a measure of the proportion of variance in the dependent variable that is attributable to the independent variable(s). This statistic ranges from 0 to 1, where 0 indicates no effect and 1 indicates a perfect association. The normality of distribution for residuals in the GLM was verified using the Shapiro-Wilk test, supplemented by an evaluation of skewness. A threshold of less than 3.3 for both kurtosis to standard error ratio and skewness to standard error ratio was adopted as a criterion for normality, in line with the guidelines proposed by (Tabachnick & Fidell 2006).

Following recommendations by (Kim et al., 2020), this study employed mixed-effects models to account for the hierarchical structure of the data and the heterogeneity in treatment effects across different soil types and environmental conditions. This criterion ensures that the data adequately meets the assumptions of normality required for reliable GLM analysis. Furthermore, Pearson's correlation coefficient was calculated to explore the linear relationships between soil and plant parameters, providing insights into how these variables interrelate within the experimental framework.This comprehensive statistical approach, grounded in robust statistical theory and practices, underpins the reliability and validity of the findings derived from the study.

4. RESULTS AND DISCUSSION

4.1 Evaluation of the Single Cover Crop Species

4.1.1 Productivity of Cover Crop Species in Different Soil Types

The impact of cover crops on soil parameters and biomass was substantial, as highlighted in the statistical analysis results. The General Linear Model (GLM) analysis reflected significant variances among the treatments ($F (16,36) = 16.92$; $P < 0.001$; Wilk's $\lambda = 0.00$; partial $\eta2 = 0.81$), indicating a robust influence of cover crops on the measured soil and biomass variables.

Greenhouse Pot Experiment (Arenosols Soil):

In the greenhouse pot experiment using Arenosols soil, four replications per treatment were conducted to ensure statistical validity. The broad bean (*Vicia faba*) cover crop exhibited the highest dry biomass production among all treatments ($P < 0.05$), as depicted in *Figure 7*. This significantly higher biomass production highlights the vigorous growth of broad beans in the controlled environment and its potential for contributing substantial organic matter to the soil. Conversely, the control treatment, where no cover crops were planted, resulted in the lowest biomass accumulation, underscoring the positive impact of cover crops on biomass production in Arenosols soil. The double symbiotic broad bean treatment led to the highest dry biomass among all treatments, differing significantly from the other cover crops ($P < 0.05$). In stark contrast, the control treatment without any cover crops resulted in the lowest biomass production.

The significant increase in dry biomass production associated with the broad bean treatment could be a result of the combined effects of improved soil fertility, increased microbial activity, and enhanced mycorrhizal associations. These findings support the hypothesis that cover crops can improve the subsequent crop's growth and yield by improving soil quality (Teasdale et al., 2008).

Comparison of Cover Crop Performance:

Comparing the performance of individual cover crops across the Pot experiment, the performance of individual cover crop species varied significantly across experimental setups, the broad bean cover crops in the greenhouse experiment consistently demonstrated superior biomass production. Specifically, in the greenhouse experiment, the broad bean cover crop exhibited significantly higher dry biomass production than all other treatments, including mustard, oat, phacelia, and vetch ($P<0.05$) (*Figure 7*). which can be attributed to its symbiotic nitrogen-fixing ability and compatibility with Arenosols. In the field experiment, lentils showed outstanding performance compared to other single species and followed by mixed CC (*Figure 7*). While the species differed between the two experiments, both are leguminous cover crops known for their ability to fix nitrogen and accumulate substantial biomass.

The mixed cover crop treatment showed the second-highest biomass production in the field experiment, indicating the potential benefits of cover crop mixtures in field conditions. Other cover crops, such as mustard, oat, phacelia, and vetch in the pot experiment, compared to broad bean.

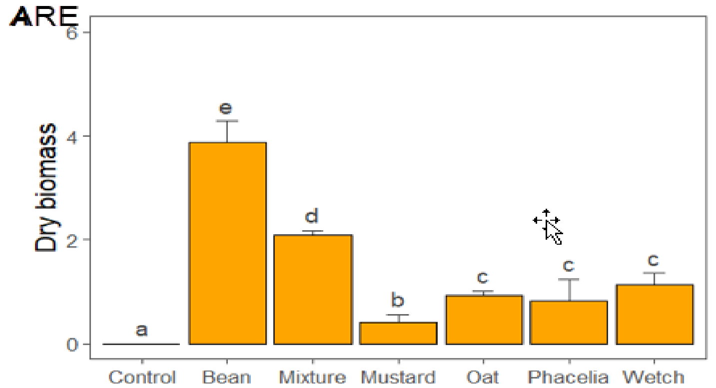

Figure 7 Dry biomass production of different cover crop species in Greenhouse pot experiment on Arenosols soil. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using p p post-hoc test (P<0.05)

4.1.2 Effect of Cover Crops on Soil Properties in Pot Experiment

Greenhouse Pot Experiment (Arenosols Soil):

The statistical evaluation demonstrated that cover crops exerted a considerable effect on various soil parameters and plant biomass. A General Linear Model analysis confirmed these differences as statistically significant ($F (16,36) = 16.92$; $P < 0.001$), with Wilk's lambda indicating a substantial combined effect on all studied variables (Wilk's $\lambda = 0.00$; partial $\eta 2 = 0.81$). This high partial $\eta 2$ value reveals that the presence of cover crops had a strong influence on all seven of the independent variables under study.

Figures 8 consists of four parts. *1A, 1B, 1C,* and *1D* visualize the observed significant disparities among the cover crop treatments:

Figure8. 1A illustrates that oat cover crops led to the highest soil NH_4^+ content, with a statistically significant difference compared to the other cover crops ($P < 0.05$). The cover crop mix, mustard, and phacelia treatments were statistically indistinguishable from one another ($P > 0.05$). Similarly, no significant differences were noted between phacelia and vetch treatments ($P > 0.05$), with both exhibiting lower NH_4^+ values compared to the broad bean treatment. The broad bean treatment and phacelia cover crop showed the second highest NH_4^+ content, while the untreated control had the lowest.

Figure8. 1B presents that the broad bean cover crop harbored the most substantial soil NO_3^- content, with significant distinctions from all other cover crops, except for the mixed cover crop treatment ($P < 0.05$). The mixture treatment surpassed the control but did not differ significantly from the remaining treatments ($P > 0.05$). Mustard, oat, phacelia, and vetch treatments were equivalent in their NO_3^- content ($P > 0.05$), and the control maintained the lowest NO_3^- levels.

The increase in soil NH_4^+ and NO_3^- concentrations under certain cover crops, notably oats and broad beans, underscores the role of these crops in enhancing soil nutrient availability. These results are consistent with the assertions of (Thorup-Kristensen et al.,2003), who found that deep-rooted cover crops could scavenge nutrients from deeper soil layers and make them available to subsequent crops. The increase in nutrient availability is likely due to the biotic and abiotic processes facilitated by the cover crops, such as nitrogen fixation by leguminous plants and the decomposition of organic matter, which releases nutrients into the soil (Clark et al., 2007).

Figure8. 1C depicts that the broad bean treatment exhibited the highest N_{min} concentration, standing out significantly from the control and vetch treatments ($P < 0.05$). The mixed cover crop treatment showed an elevated N_{min} concentration compared to the control, albeit not to a significant degree ($P > 0.05$). The mustard, oat, phacelia, and vetch treatments were statistically similar in N_{min} content ($P > 0.05$), with the untreated control presenting the lowest values.

Figure8. 1D reveals no statistically significant differences in EC values among the broad bean, mixture, mustard, oat, phacelia, and vetch treatments ($P > 0.05$). The control treatment, however, registered a significantly lower EC value than the other mentioned treatments ($P < 0.05$), denoting the influence of cover crops on soil electrical conductivity.

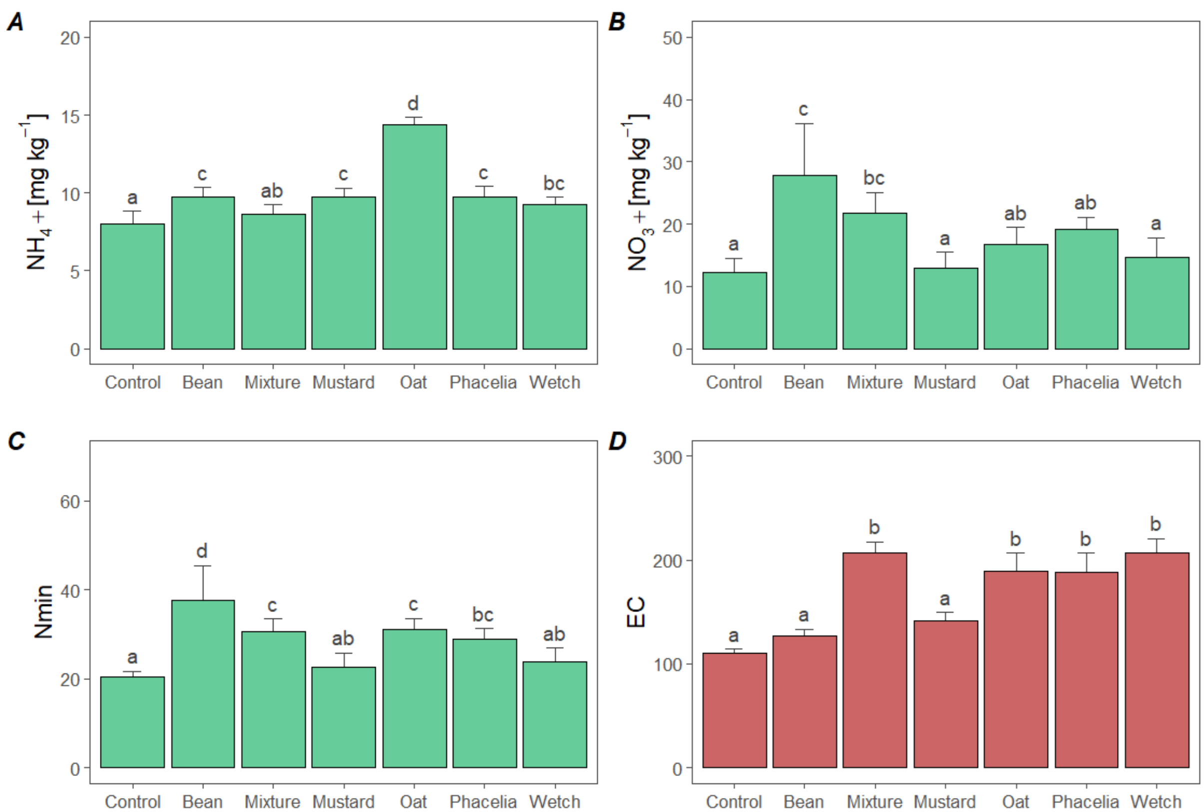

Figure 8 Effect of cover crops on soil characteristics. A) NH_4^+, B) NO_3^- , C) N_{min}, B) EC. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using post-hoc test ($P<0.05$)

The detailed statistical measures for each independent variable, including the F-values, partial eta squared values, and degrees of freedom, are systematically documented in Appendix 1. Notably, the highest observed effect size was associated with dry biomass, succeeded by mycorrhizal colonization and soil NH_4^+ content, with the partial η2 suggesting that these variables were considerably affected by the cover crop treatments, exhibiting a 93-96% influence.

The results elucidated by *Figure 8*, which showcased the influence of cover crops on soil nutrient dynamics and electrical conductivity, provide the foundation to appreciate the interconnected results presented in *Figure 8*. These latter findings further elaborate on the multidimensional impact of cover crops, specifically their role in soil enzyme activity, mycorrhizal colonization, and overall biomass production that complementing the findings related to soil nutrient content presented earlier.

Figure 9. 2B reveals that the mixture treatment exhibited the highest fluorescein diacetate (FDA) hydrolysis activity, suggesting enhanced microbial activity compared to the control, which showed the lowest activity. Significant differences were observed between the control and all other treatments, except mustard and phacelia, which indicates a trend where mixed cover crops may promote a more active microbial environment.

Figure 9. 2C illustrates that both the broad bean and mixture treatments achieved the highest levels of mycorrhizal colonization, significantly higher than those observed in the mustard and control treatments. This underlines the potential of certain cover crops to foster beneficial symbiotic relationships between plants and soil fungi. The observed variations in FDA hydrolysis activity among the treatments may reflect differences in soil microbial communities and enzyme production, which are influenced by the presence and type of cover crops (Bossio et al., 1998). The mixture treatment showing the highest FDA activity suggests a synergistic effect of plant diversity on microbial functions, a phenomenon that has been documented in previous studies (Drinkwater et al., 1995). This increase in microbial activity could contribute to the cycling of nutrients and improve soil structure (Six et al., 2000).

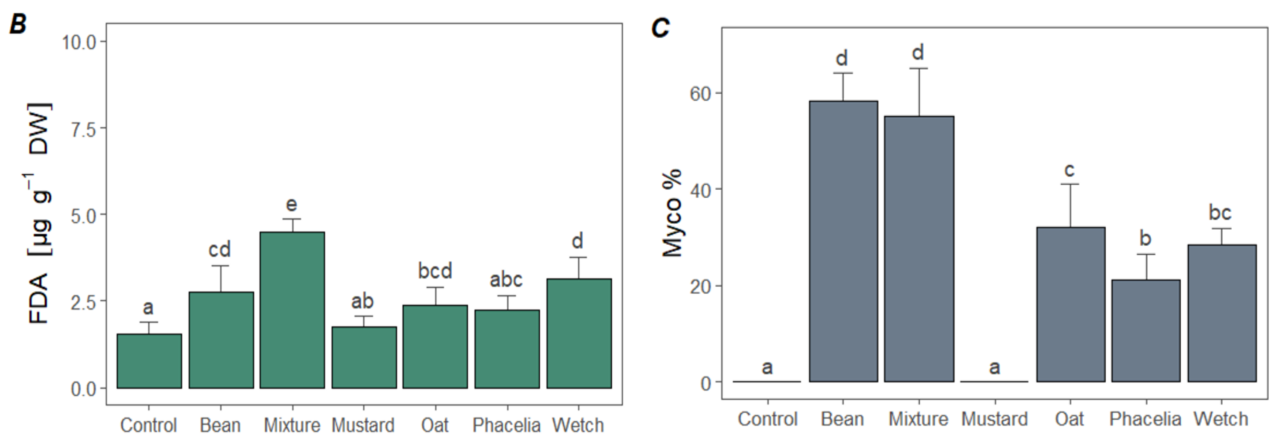

Figure 9 Effect of cover crops on soil characteristics and biomass production. B) FDA, C) Myco %. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Dunc post- -hoc test (P<0.05)

Connecting these findings with the previous results, it is evident that cover crops have a pronounced effect on soil parameters, including nutrient content (NH_4^+ and NO_3^-), electrical conductivity, microbial activity, and the biological aspect of soil health, represented by mycorrhizal colonization. These variables, in turn, are closely associated with plant biomass production, as evidenced by the substantially higher biomass yields in treatments with cover crops, particularly the broad bean treatment. The significant differences noted across various parameters emphasize the value of cover crops in enhancing soil quality and plant growth. The strong effects measured by partial eta squared (η2) values and the diverse responses in FDA hydrolysis and mycorrhizal colonization across treatments suggest that the choice of cover crop is crucial for optimizing soil health and productivity.

4.2 Field Experiment Results and Their Complementarity to Pot Experiment

4.2.1 Cover Crop Performance Under Field Conditions

Field Experiment (Inceptisols Soil):

The field experiment conducted on an agricultural site of Tishreen University in Latakia city, Syria (35.5167° N, 35.7833° E), using Inceptisols soil, the lentil (*Lens culinaris*) cover crop demonstrated significantly higher dry biomass production compared to other treatments (P < 0.05), followed by the mixed cover crop treatment, as shown in *Figure 10*. The control group in this experiment also produced the least biomass, consistent with the findings from the greenhouse experiment.

Comparison of Cover Crop Performance:

In the field experiment, indicating the potential benefits of cover crop mixtures in field conditions. Other cover crops, such as clover, rapeseed, and rye in the field experiment, exhibited lower biomass production compared to lentil. The mixed species treatment ranked second, suggesting that functional complementarity among species can enhance above-ground biomass production even under variable environmental conditions. In contrast, the control plots (non-planted) recorded the lowest biomass, emphasizing the agronomic importance of implementing cover crops in fertility-depleted or previously uncultivated soils. Other species such as *Trifolium* spp. (clover), *Brassica napus* (rapeseed), *Raphanus sativus* (radish), and *Secale cereale* (rye) produced moderate to low biomass, potentially due to suboptimal adaptation to soil or climate constraints.

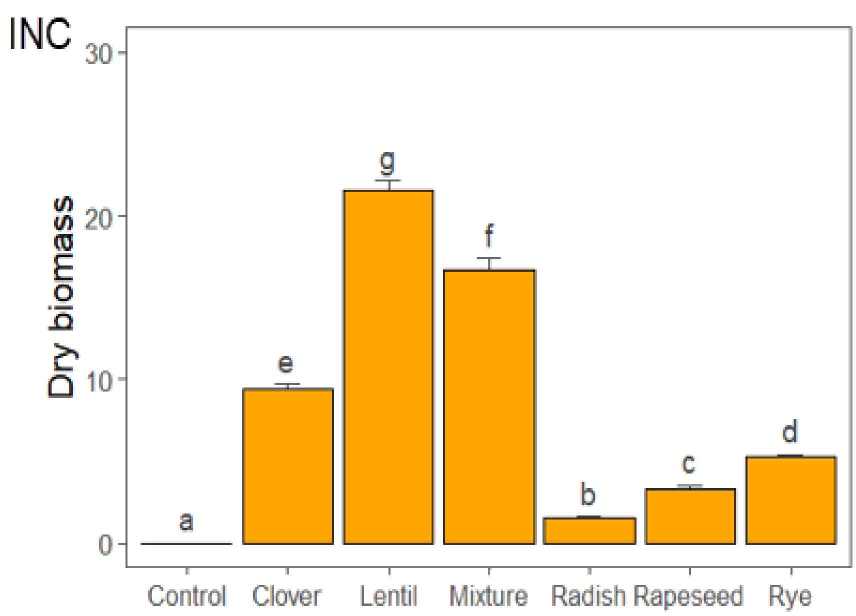

Figure 10 Dry biomass production of different cover crop species in field experiments on Inceptisols soils. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using post-hoc test (P<0.05)

4.2.2 Soil Property Changes in Field vs. Controlled Environments

The field experiment conducted to investigate the effect of various cover crops on soil characteristics and biomass production yielded significant results ($F\ (16,36) = 18.92$; $P<0.001$; Wilk's $\lambda= 0.00$; partial $\eta2=0.80$). These results provide evidence for the substantial role of cover crops in altering soil chemical properties. *Figures 11 3A to 3D* illustrate these significant differences, with a strong effect observed on the measured independent variables. The field experiment conducted in Syria provided valuable insights into the effect of cover crops on soil fertility and structure. Our findings corroborate the hypothesis that the incorporation of cover crops into cropping systems significantly alters soil characteristics, enhancing nutrient content and potentially influencing soil conductivity.

As depicted in *Figure11. 3A*, the soil NH_4^+ content reached its zenith in plots treated with the Mixture cover crop, markedly surpassing the levels found in all other cover crop treatments ($P<0.05$). Notably, Clover, Lentil, and Rye treatments exhibited comparably higher NH_4^+ concentrations, though none matched the Mixture treatment's peak. The Control plots registered the lowest NH_4^+ concentrations, significantly trailing behind the Lentil, Mixture, and Rye treatments ($P<0.05$).

In a similar vein, *Figure11. 3B* indicates that the Mixture and Lentil treatments led to the most substantial NO_3^- concentrations, significantly outstripping those of the other treatments ($P<0.05$). This suggests a potential enhancement in soil nitrogen availability due to these specific cover crops. Conversely, the Control plots were characterized by the least NO_3^- concentration, significantly lower compared to the other treatments ($P<0.05$). The examination of total mineral nitrogen content.

In *Figure 11. 3C* reinforces the trend observed in NH_4^+ and NO_3^- concentrations. The Mixture and Lentil treatments significantly outperformed all other treatments in N_{min} content ($P<0.05$), further corroborating the nitrogen-enriching effect of these cover crops. The Control plots, with the lowest N_{min} content, demonstrated a clear distinction from the nutrient-enriched plots ($P<0.05$). The enhanced N_{min} content observed in the mixture and lentil treatments is indicative of increased nitrogen availability, which is critical for the growth of subsequent crops. This finding supports the research by (Clark et al., 2007), who found that leguminous cover crops such as lentils could contribute significantly to the nitrogen economy of agricultural systems through biological nitrogen fixation.

Figure 11. 3D presents a nuanced picture of soil electrical conductivity across treatments. The Rapeseed treatment exhibited the highest EC values, significantly differing from the rest ($P<0.05$), potentially indicating greater soluble salt concentrations or enhanced ionic mobility in the soil solution. Meanwhile, the Control, Clover, and Lentil treatments did not significantly differ in EC values ($P>0.05$), suggesting similar levels of soil salinity and nutrient solubility. The increased EC values in the rapeseed treatment plots might be indicative of higher mineral ion concentrations in the soil solution, which can be both beneficial and detrimental, depending on the specific ions and crop needs. It is essential to balance EC levels to prevent potential salinity issues that could arise, especially in regions like Syria (Qadir et al., 2014).

The high partial η^2 values observed, ranging from 93% to 100%, underscore the strong influence cover crops exert on soil chemical properties. The implications of these findings are particularly relevant for sustainable agricultural practices that seek to optimize soil health and productivity. The comprehensive data derived from these field tests and their statistical significance are thoroughly detailed in Appendix 2, providing a clear and systematic overview of the treatment effects on soil properties.

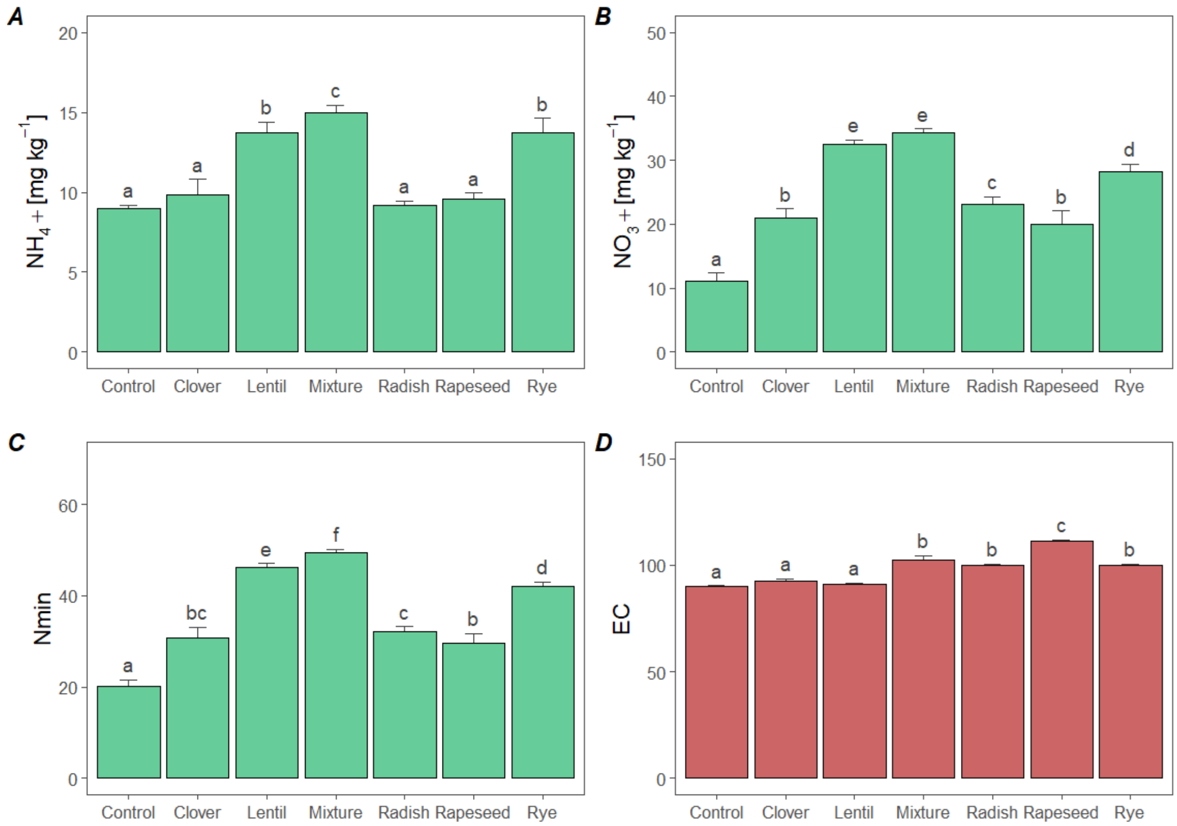

Figure 11 Impact of Cover Crops on Key Soil Parameters in a Field Experiment. A) NH_4^+, B) NO_3^- , C) N_{min}, B) EC. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

Figure 12 highlights the differential effects of various cover crops on soil enzyme activity, mycorrhizal colonization, and biomass production in a field setting. In panel A, lentil cover crops stand out, producing significantly higher dry biomass compared to other treatments (P<0.05), followed by the mixed cover crop. Notably, the control group demonstrated the least biomass production. Panel B reveals that the lentil and mixture treatments elicited the strongest FDA hydrolysis activity, indicative of vigorous soil microbial activity, with the control treatment showing the lowest levels. Mycorrhizal colonization, depicted in panel C, follows a similar pattern, where lentil and mixture treatments fostered greater symbiotic relationships compared to the other cover crops. The Duncan post-hoc test (P<0.05) results, detailed by alphabetical letters above the bars, affirm these significant differences across the treatments. Mycorrhizal colonization percentages being higher in these treatments suggest an enhanced symbiotic relationship that is vital for nutrient uptake and plant health. This finding is particularly noteworthy, given the arid conditions in Syria where efficient water and nutrient uptake are critical for plant survival and productivity (Smith & Read, 2008).

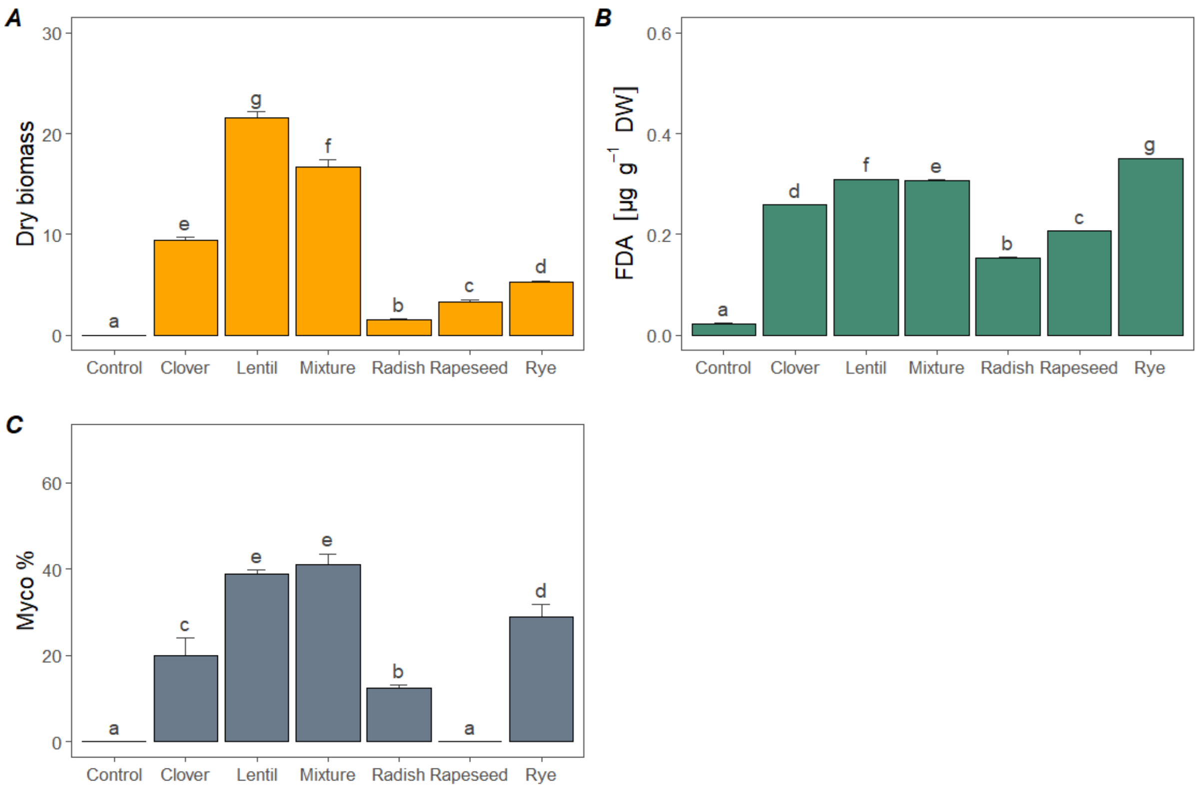

Figure 12 Effect of cover crops on soil characteristics and biomass production. A) Dry biomass B) FDA, C) Myco %. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Dunc post-hoc test (P<0.05).

The field experiment conducted in Syrian soils provided insightful data on the influence of cover crops on various agricultural parameters. The results corroborate the notion that cover crops, particularly lentils and diverse mixtures, can markedly enhance soil health, as evidenced by increased FDA hydrolysis activity, which is a proxy for microbial activity and nutrient cycling efficiency (Drinkwater et al., 1995). n this experiment, soil structure was indirectly assessed using POXC (Permanganate Oxidizable Carbon) and MYCO% (mycorrhizal colonization), both closely linked to soil aggregation and biological structure. Higher POXC and MYCO% values in legume and mixed cover crop plots indicated improved soil structure. Additionally, better root development and soil tilth were visually observed in these plots, although no direct measurements like bulk density or aggregate stability were performed. This observation aligns with prior studies that have reported enhanced soil microbial activity in the presence of legumes and diverse plant mixtures, potentially due to a combination of root exudates and nitrogen fixation properties (Berg & Smalla, 2009). The substantial increase in dry biomass production with the lentil and mixture treatments can be attributed to improved soil fertility, as indicated by the augmented N_{min} content observed in the earlier figures.

Lentils, being legumes, have the inherent ability to fix atmospheric nitrogen, enriching the soil with readily available nitrogenous compounds that are essential for plant growth (Peoples et al., 2009). Furthermore, the mixed cover crops may offer a more heterogeneous environment conducive to a variety of soil organisms, resulting in a more robust soil structure and fertility (Tilman et al., 2006). The consistently lower performance of control plots across all parameters emphasizes the necessity of cover crops in boosting agricultural outputs, especially in challenging environments. The results from this first-year field experiment provide promising insights into sustainable agricultural practices that can potentially reduce reliance on chemical fertilizers, improve crop yields, and foster soil biodiversity. Combining the discussions from *Figures 11 and 12*, the field experiment in Syria paints a holistic picture of how cover crops may influence soil chemistry, microbial life, and plant growth. The consistent trends across these independent variables—across different cover crop treatments—reaffirm the positive role of cover crops in sustainable agricultural systems. This is particularly relevant for regions facing environmental stresses, where optimizing natural processes can lead to more resilient farming practices. As these are first-year results, continued research is necessary to understand the long-term impacts and to evaluate the consistency of these effects over multiple growing seasons.

4.2.3 Cross-Contextual Comparison: Hungary Greenhouse vs. Syrian Field Trials

To bridge the gap between controlled experimental findings in Hungary and practical field applications in Syria, a comparative framework was developed. The following table 7 summarizes key insights, illustrating how outcomes from the pot experiment informed the selection, timing, and management of cover crops under Syrian field conditions.

Table 7. Comparison of Pot (Hungary) and Field (Syria) Cover Crop Experiments

Parameters	Pot Experiment (Hungary)	Field Experiment (Syria)
Soil Type	Arenosols (sandy, low fertility, neutral pH)	Inceptisols (slightly acidic to neutral, low horizon development)
Environment	Controlled greenhouse (stable temperature and humidity)	Open field (Mediterranean climate, variable conditions)
Main Legume Species	*Vicia faba* (broad bean)	*Lens culinaris* (lentil)
Other Cover Crops	Phacelia, Oat, Mustard, Vetch, Mix	Clover, Rapeseed, Radish, Rye, Mix
Biomass Leader	*Vicia faba*	*Lens culinaris*
Strongest Mix Treatment	Moderate biomass, high FDA & Myco	Second-best biomass, high N_{min} & microbial activity
Symbiosis Focus	Species selected for high rhizobial/mycorrhizal potential	Adapted species; less emphasis on symbiosis
Most Improved Soil Parameter	NH_4^+ and FDA under *Vicia faba*	N_{min} and Myco under Lens culinaris
Experimental Duration	8 weeks	10 weeks
Key Findings	Symbiotic legumes highly enhance soil biology	Legumes & mixes improve N and microbial resilience

The controlled pot experiment conducted in Hungary provided a foundational understanding of how individual cover crop species, particularly legumes like *Vicia faba*, influence soil biological, chemical, and physical parameters under ideal conditions. These findings offer a mechanistic baseline that can be adapted and applied to the Syrian context. In Syria, where the environmental conditions are more variable and often constrained by water scarcity and soil degradation, insights from the Hungarian study serve as a valuable predictive framework. For example, the superior performance of *Vicia faba* in Arenosols due to its symbiotic nitrogen fixation and stimulation of microbial activity informed the selection of analogous leguminous species like *Lens culinaris* (lentil) for the field trials on Inceptisols.

Moreover, the Hungarian study highlighted the timing and magnitude of microbial responses (e.g., FDA and Myco%), which can guide cover crop termination strategies in Syria to synchronize peak soil activity with main crop demands. While the species combinations in Hungary were selected for high symbiotic potential, the field experiment in Syria demonstrated how these ecological functions perform under real-world constraints. Thus, the Hungarian experiment did not only serve as a proof of concept but also helped develop a context-specific, evidence-based framework for sustainable cover cropping in semi-arid Mediterranean systems like those in Syria. The cover crop species used in the Hungarian pot experiment were selected for their suitability to controlled greenhouse conditions and Central European soils. In contrast, the Syrian field experiment required species that are adapted to Mediterranean climate, limited rainfall, and local soil types (Inceptisols). Therefore, species selection for Syria focused on crops with proven drought tolerance, local availability, and farmer familiarity, such as lentil, clover, and rapeseed. Using the same species from Hungary would not have guaranteed successful establishment or realistic results under Syrian field conditions.

4.3 Effects of Cover Crop Treatments Over Two Years

Mix 1 (MIX1) comprised Italian ryegrass (*Lolium multiflorum*), purple vetch (*Vicia benghalensis*), and peas (*Pisum sativum*). aiming to investigate the effects of diverse symbiotic interactions within the same soil environments. Mix 2 (MIX2) was a combination of the three single cover crops: *Brassica carinata*, *Vicia faba*, and *Avena strigosa*. intended to assess the collective impact of their symbiotic traits when grown together. For the control group during this phase, pots were prepared but left unplanted to serve as a baseline for comparison against the cover-cropped soils. Fifteen seeds from each respective cover crop and mixture compositions were sown in pots containing one of three soil types: Arenosols, Chernozems, and Luvisols. These were managed in a heated greenhouse under controlled conditions, with an average temperature setting of 19°C during the day and 10°C at night, complemented by a constant humidity level of 52%. The growth period lasted for eight weeks, after which the biomass of each cover crop treatment, including MIX1 and MIX2, was harvested and quantified in terms of both fresh and dry weights of root and shoot biomass.

4.3.1 Comparative Performance of Cover Crops by Biological Parameters

The investigation into the effect of cover crops on biomass production across different soil types over consecutive years yielded statistically significant results. General Linear Model (GLM) analysis revealed significant impacts attributable to cover crop types ($F (35,368) = 47.92$; $P < 0.001$; partial $\eta 2 = 0.76$), soil type ($F (14,174) = 243.94$; $P < 0.001$; partial $\eta 2 = 0.95$), and the year of study ($F (7,87) = 48.35$; $P < 0.001$; partial $\eta 2 = 0.79$). Notably, interactions between these factors were also significant, including the interaction between cover crop and year ($F(28,315) = 2.45$; $P < 0.001$; partial $\eta 2 = 0.16$), year and soil type ($F(14,174) = 3.78$; $P < 0.001$; partial $\eta 2 = 0.23$), and a three-way interaction amongst year, cover crop, and soil type ($F(56,473) = 2.25$; $P < 0.001$; partial $\eta 2 = 0.166$). Detailed results of the GLM model for the main effects and interactions are systematically presented in Appendices 3 and 4.

Figure 13 portrays the influence of cover crops on biomass production for the two years studied. During the first year, the MIX2 cover crop achieved significantly higher biomass in Arenosols than all other cover crop types (P < 0.05). This trend persisted into the second year and was consistent across the other soil types, with MIX2 and broad beans consistently yielding the highest total biomass. Notably, oats and mustard did not show significant increases in biomass, suggesting a limited effect of these crops in the tested soil conditions or pot environment. For Luvisols, MIX2 again led in biomass production, suggesting its potential as a resilient and adaptable cover crop mix capable of thriving across diverse soil types. The substantial variance in biomass production across different cover crops and soil types over two consecutive years suggests that the selection of cover crops is paramount and should be tailored to the specific soil characteristics to optimize biomass production.

The significant interaction effects observed imply that cover crops do not operate in isolation but interact with soil properties and temporal factors to affect biomass outcomes (Drinkwater et al., 1998). Cover crop mixtures (MIX1 and MIX2) combining legumes and non-legumes displayed synergistic effects. These treatments yielded intermediate to high biomass while enhancing soil biological functions.

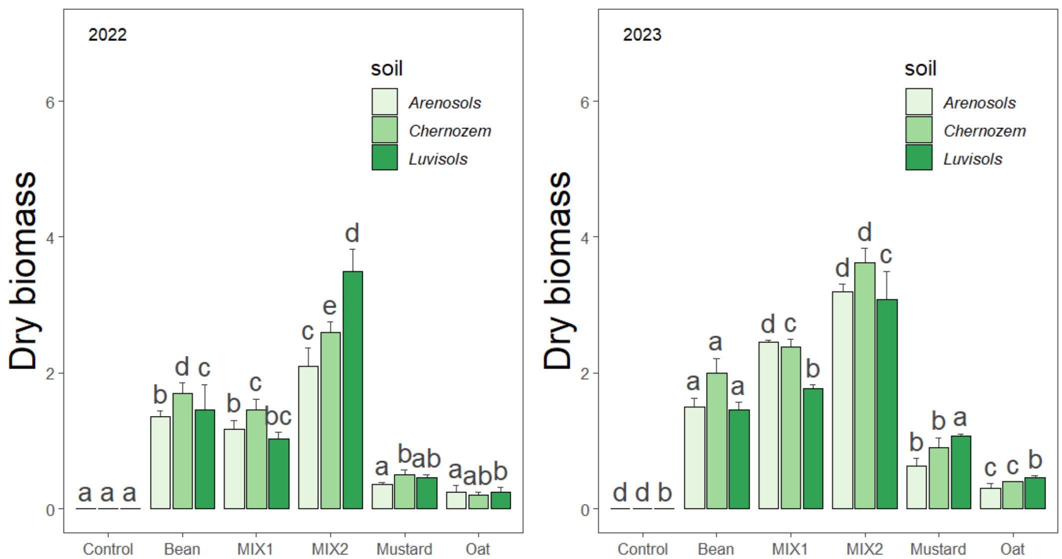

Figure 13 The effect of cover crops on biomass production on different soil types in two years. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The MIX2 cover crop's consistent outperformance across soil types could be indicative of its composition, potentially offering a diverse array of plant traits that synergistically improve soil conditions (Tilman et al., 2006). The strong performance of leguminous broad beans further emphasizes the importance of nitrogen-fixing plants in cover crop strategies, especially in soils like Chernozem, known for their high fertility and organic matter content. Moreover, the significance of soil type in determining the effectiveness of cover crops is underscored by the distinct responses of Arenosols, Chernozem, and Luvisols.

This specificity highlights the need for localized cover crop management strategies that consider the inherent properties of the soil (Lal, 2004). The annual variation in biomass production also suggests that cover crop benefits may evolve over time, potentially increasing as soil properties are progressively improved or as cover crops establish more complex interactions with soil biota (Kremen & Miles, 2012). The significant three-way interaction indicates that these dynamics are multifaceted and can be influenced by a range of agronomic and environmental factors.

Figure 14 illustrates that, irrespective of the year, broad bean, MIX1, and MIX2 consistently exhibited the highest mycorrhizal colonization across all soil types, reinforcing the role of cover crops in fostering beneficial fungal associations. Notably, mustard showed an incremental increase in Myco% in the second year, indicating a potential adaptation or cumulative effect over time. The control and mustard treatments generally resulted in the lowest colonization rates, highlighting the importance of cover crops in promoting mycorrhizal relationships. The pronounced colonization in broad bean cover crops aligns with existing literature that legumes are particularly effective at forming mycorrhizal associations due to their ability to supply carbon compounds to the fungi through photosynthesis (Smith & Read, 2008).

The mixture treatments likely provide a diversity of root exudates and plant signals that can select for a rich community of mycorrhizal fungi, echoing the findings of van der (Heijden et al., 1998), who reported enhanced biodiversity in polyculture systems. In 2023, EC values increased for broad beans in Luvisols, following the previous year's trend, and the lowest EC values were consistently observed in Arenosols across all cover crop treatments. The lower EC values in Arenosols could be due to its sandier texture, which typically holds fewer nutrients and thus exhibits lower conductivity (Brady & Weil, 2008). The consistent low EC in Arenosols may also point to the inherent challenges of managing fertility in sandy soils.

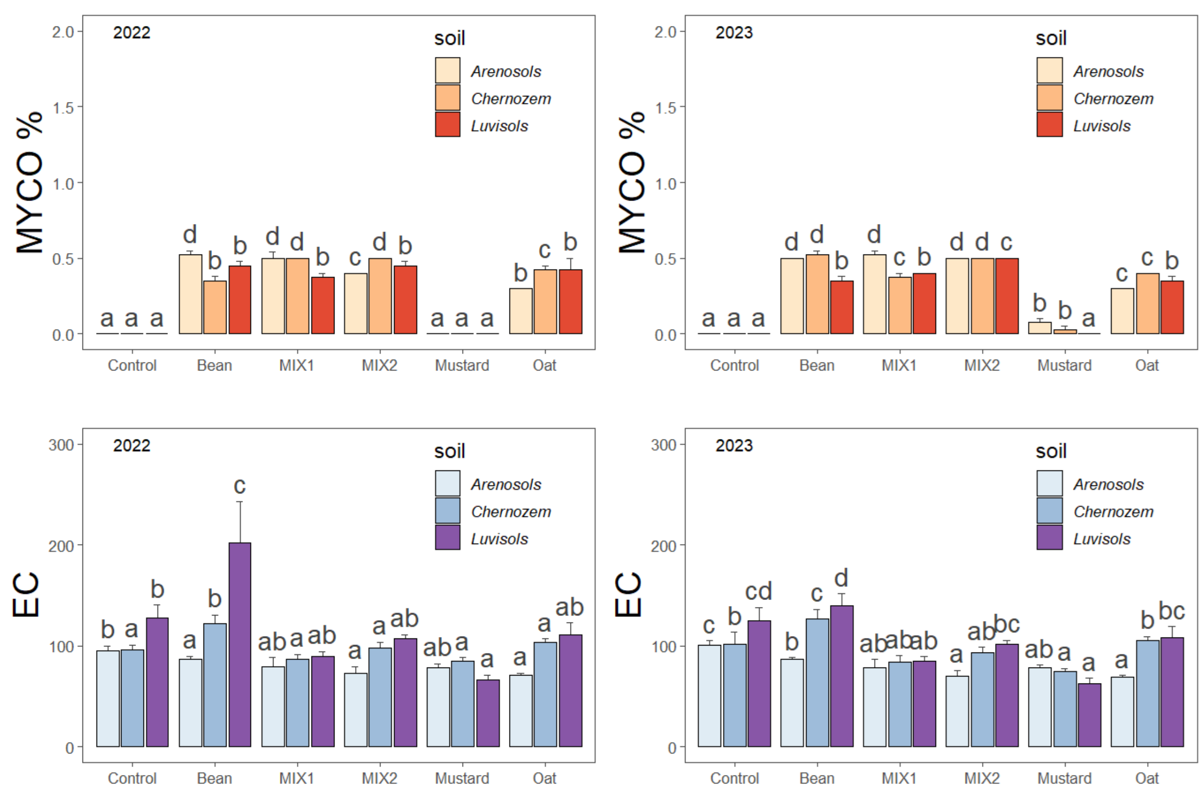

Figure 14 The effect of cover crops on Myco% and EC on different soil types in two years. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05)

The robustness of broad bean, MIX1, and MIX2 in enhancing Myco% across different soil types and years points to their potential utility in soil health management strategies. Moreover, mycorrhizal colonization was most pronounced in mixtures containing both legumes and cereals, revealing that combining root exudate types and root architectures can enhance symbiotic interactions. Such traits make cover crop mixtures ideal candidates for improving resilience in variable field conditions. The observed increase in EC in Luvisols under broad bean cover crops could have implications for nutrient management, as EC is a proxy for nutrient availability to plants. The increased EC in the second year might also indicate an accumulation of soluble salts or a change in soil chemistry that could have long-term implications for soil health and fertility management. The slight increase in Myco% for mustard in the second year suggests that cumulative effects of cover cropping may take time to manifest, an aspect that warrants further investigation in long-term studies. These findings emphasize the necessity of considering both immediate and delayed responses of soil properties to cover cropping.

Evaluation of cover crop influence on permanganate oxidizable carbon and fluorescein diacetate hydrolysis over two years: This pot experiment conducted over two consecutive years assessed the effects of various cover crops on soil biochemical parameters, namely Permanganate Oxidizable Carbon (POXC) and Fluorescein Diacetate (FDA) hydrolysis, in three different soil types.

In 2022, broad bean treatment markedly elevated POXC in Arenosols, surpassing that in the control, mustard, and oat treatments significantly ($P<0.05$) in *Figure 15*. MIX2 also demonstrated enhanced POXC, comparable to broad beans but not significantly different ($P>0.05$), indicating its potential as an effective soil ameliorant. MIX1's POXC values were notably higher than the control, mustard, and oat, suggesting its contribution to soil carbon pools. Mustard and oat did not significantly differ from the control, which may point to their lesser influence on labile carbon. For Chernozem, MIX2 stood out with the highest POXC, potentially indicative of improved soil quality through the incorporation of diverse plant residues.

In Luvisols, MIX1 and MIX2 led to the highest POXC, again underscoring the efficacy of mixed cover crops in enhancing soil carbon content. Moving to 2023, both broad bean and MIX2 treatments maintained high POXC in Arenosols, reflecting their consistent contribution to soil carbon over time. Similar trends were observed in Chernozem and Luvisols, where MIX1 and MIX2 resulted in high POXC, reinforcing the previous year's patterns. These findings are aligned with the literature that suggests diverse cover cropping systems can increase soil organic carbon levels, beneficial for soil structure and fertility (Lal, 2004; Poeplau & Don, 2015).

Analyzing FDA hydrolysis in 2022 reveals broad bean and MIX1 as key drivers of high enzymatic activity in Arenosols, possibly due to their root exudates and biomass inputs, which enhance microbial activity. Mustard's low activity aligns with its known biofumigant properties that may inhibit certain soil microbes (Larkin & Griffin, 2007).

In Chernozem and Luvisols, MIX1's high FDA activity highlights the role of mixed cover crops in supporting diverse and active microbial communities. In 2023, the pattern was largely consistent, with MIX2 emerging as a strong promoter of FDA activity in Arenosols, suggesting its potential to consistently enhance microbial functioning. In Chernozem, MIX1 maintained high enzymatic activity, and in Luvisols, MIX2's high FDA activity echoed its previous performance, suggesting its adaptive capacity across soil types.

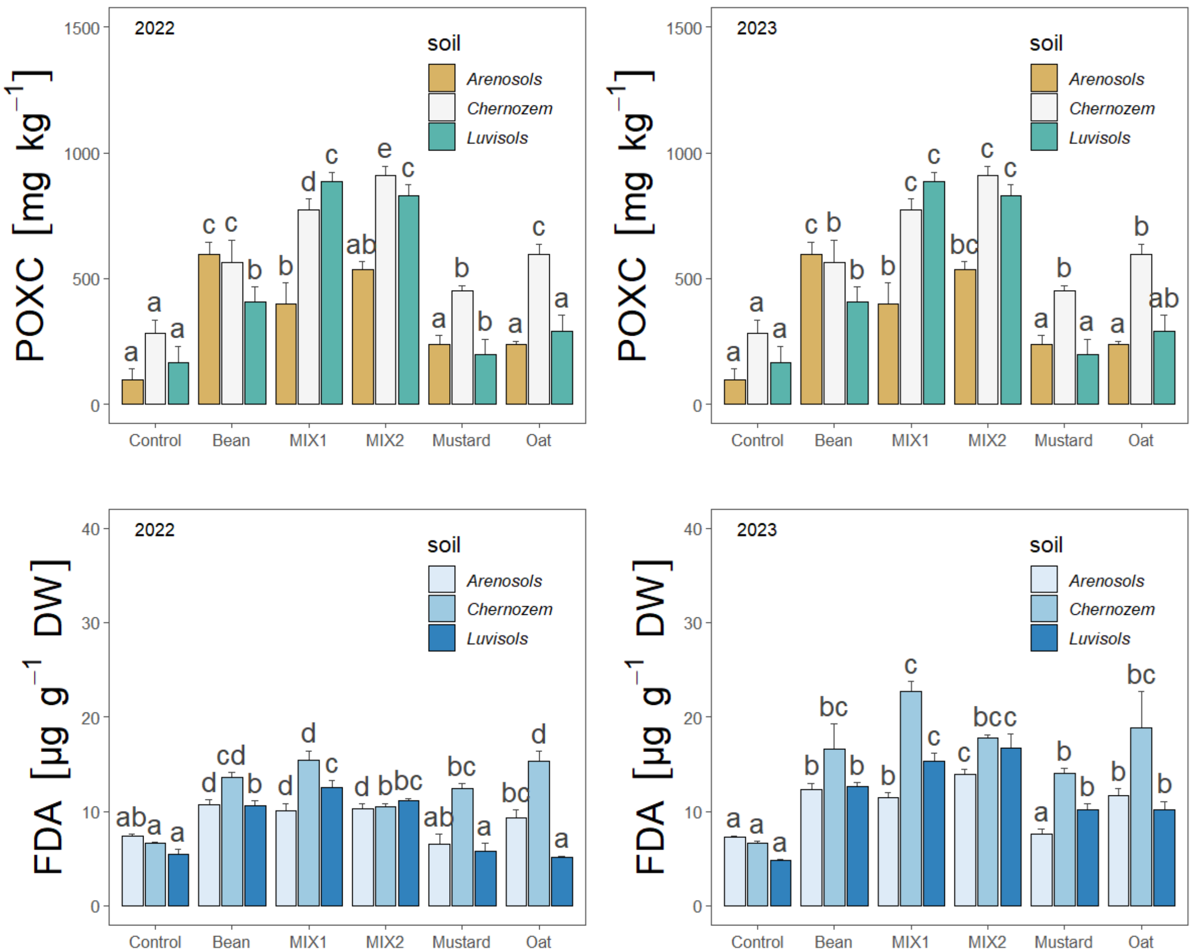

Figure 15 The effect of cover crops on POXC and FDA on different soil types in two years. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05)

The two-year comparison elucidates the positive and sustained impact of certain cover crops on both labile carbon and soil enzyme activity, fundamental indicators of soil health. The superior performance of mixed cover crops, especially MIX1 and MIX2, is likely due to their ability to provide a diverse range of organic matter inputs and create a more conducive environment for soil microbial processes (Weil et al., 2003), The differential responses across soil types further underscore the importance of matching cover crop strategies to specific soil properties to maximize their benefits (Kremen & Miles, 2012). The consistently lower values observed in the control plots throughout the study period support the premise that the absence of cover crops may lead to poorer soil biochemical properties, potentially affecting long-term soil productivity and resilience.

4.3.2 Comparative Performance of Cover Crops by Soil chemical Parameters

The study investigated the impact of various cover crop treatments on nitrogen availability in three distinct soil types over the course of two years. The evaluation focused on soil (NH_4^+) and (NO_3^-) content, as well as the total mineral nitrogen (N_{min}), considering the influence of cover crops, soil type, and temporal dynamics.

Ammonium (NH_4^+) Content Dynamics:

The 2022 findings (*Figure 16*) indicated that the MIX1 and MIX2 treatments notably enhanced NH_4^+ concentrations in Arenosols, suggesting that mixed cover crops can effectively augment the nitrogen pool, essential for subsequent crop growth. In contrast, the control and mustard treatments lagged, reflecting minimal influence on nitrogen enrichment. In Chernozem soils, the MIX2 treatment stood out, demonstrating its adaptability across fertile soil types. Luvisols benefited from MIX2 as well, reinforcing the cover crop mix's role in improving nitrogen availability in various soil conditions. The 2023 data exhibited a continuity in the trends observed during the previous year. The broad bean treatment notably improved NH_4^+ content in Arenosols, while MIX1 and MIX2 maintained high nitrogen levels across soil types, affirming the consistency of mixed cover crops in promoting nitrogen cycling.

Nitrate (NO_3^-) Concentration Variability:

In 2022, MIX2 treatment's elevation of NO_3^- in Arenosols pointed towards its potential for optimizing nitrogen forms available for plant uptake. In Chernozem, both broad bean and MIX2 treatments were exemplary, likely due to their nitrogen-fixing capabilities and organic matter decomposition, respectively. Luvisols echoed these trends, with MIX2 showing superior performance. Advancing to 2023, similar patterns emerged. The broad bean treatment, especially in Chernozem and Luvisols, demonstrated strong NO_3^- values, highlighting the significance of legume-based cover crops in soil nitrogen management. The control consistently showed lower values, indicative of the necessity of cover crops for maintaining soil nitrogen levels.

Total Mineral Nitrogen (N_{min}) Correlations:

Nmin content followed similar patterns to NO_3^-, underscoring the integral relationship between these nitrogen forms. High N_{min} in treatments with elevated NO_3^- content underscores the cumulative effect of covering crops on soil nitrogen status.

The findings of this two-year study underscore the critical role of cover crop selection in soil nitrogen management. MIX1 and MIX2 treatments consistently improved nitrogen availability, potentially due to their varied plant species composition, which can offer different mechanisms of nitrogen addition and conservation (Drinkwater et al., 1998; Tonitto et al., 2006).

The consistent lower performance of the control plots across both years solidifies the importance of cover cropping in soil fertility enhancement strategies. Broad bean's performance in increasing NH_4^+ and NO_3^- concentrations aligns with the recognized ability of legumes to fix atmospheric nitrogen, thus enriching the soil nitrogen pool (Fageria & Baligar, 2005). The positive impact on soil nitrogen content observed in the mixed cover crop treatments may also be attributed to improved soil organic matter turnover and microbial activity, which facilitate nitrogen mineralization (Clark et al., 2007).

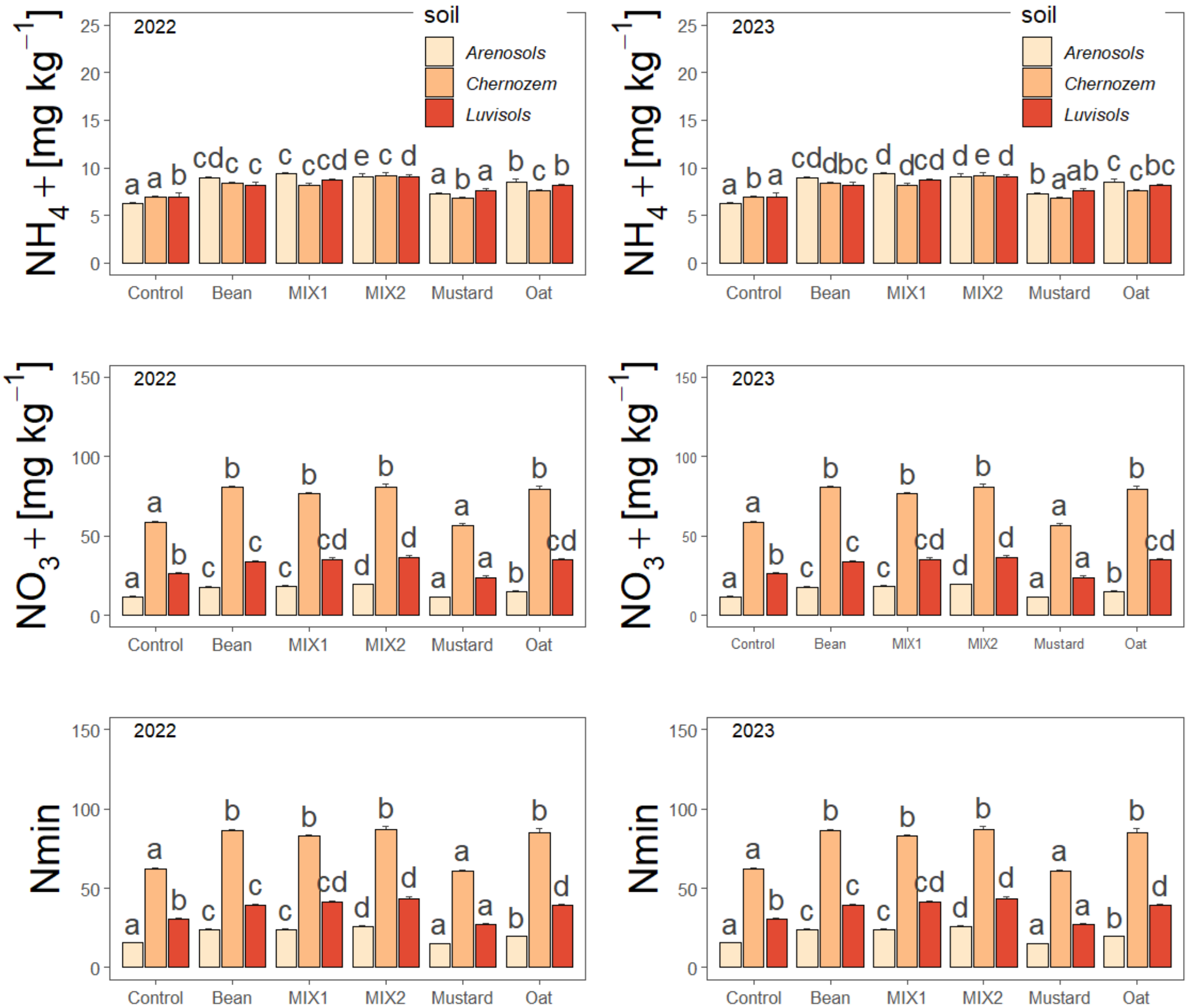

Figure 16 The effect of cover crops on nitrogen status on different soil types in two years. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05)

The influence of soil type on the efficacy of cover crops is evident, with Arenosols and Luvisols responding favorably to MIX1 and MIX2 treatments. This suggests that soil characteristics play a pivotal role in determining the success of cover crop interventions (Lal, 2004).Overall, the consistency in nitrogen enhancement across years and soil types for MIX1 and MIX2 treatments suggests that diversified cover cropping systems can offer a sustainable approach to improving soil nitrogen dynamics, which is crucial for the long-term productivity of agricultural lands. The investigation into the nitrogen dynamics and biochemical interactions in soils due to the introduction of various cover crops over two years has produced significant data, which we will now interpret in light of existing scientific knowledge.

In both years, the relationship between NH_4^+ and NO_3^- concentrations was low (r = 0.2), as shown in *Figure 17*, suggesting a weak interaction between these two forms of nitrogen in the soils studied. A moderate positive correlation between NH_4^+ and POXC (r = 0.5) implies that increased NH_4 levels may be linked to enhanced labile carbon, which could be attributed to the microbial mineralization of organic matter (Weil et al., 2003). Moreover, the strong positive correlations between NH_4^+, NO_3^-, and FDA activity (r = 0.6) indicate that higher nitrogen content is associated with increased microbial activity, corroborating the work of (Bossio et al.,1998) which showed that nutrient-rich environments promote microbial enzyme activity.

The lack of correlation between EC and other soil parameters suggests that electrical conductivity may be influenced by factors not directly related to the measured parameters in this study or that the interactions may be non-linear or complex (Larkin & Griffin, 2007).

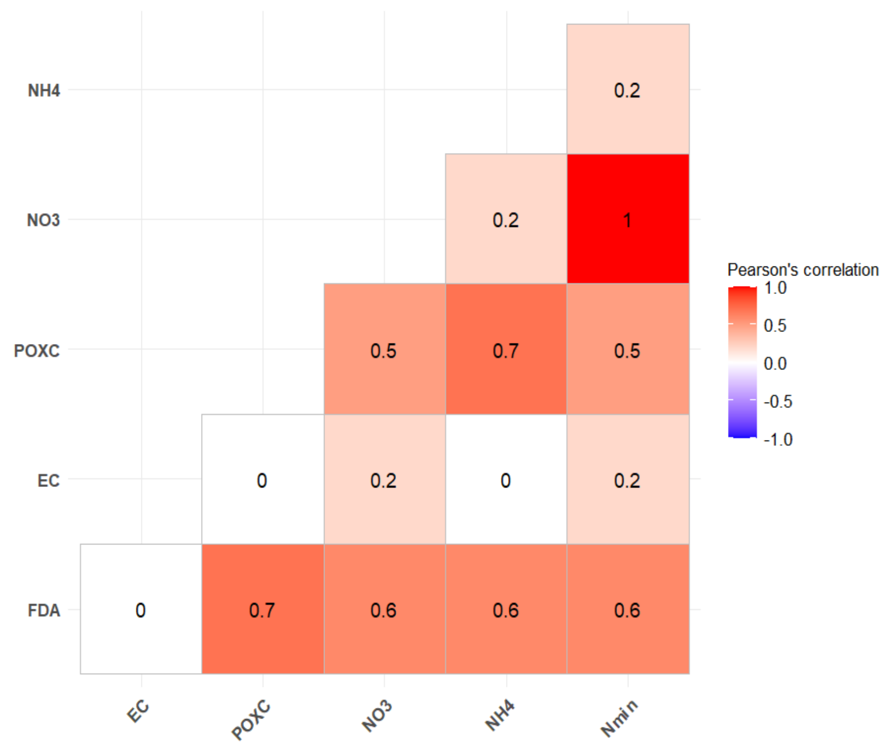

Figure 17 Pearson's correlation matrix between soil parameters. Correlations are shown in blue (positive) and red (negative); the intensity of the color is proportional to the correlation coefficient.

The MIX1 and MIX2 cover crops emerged as consistent enhancers of both NH_4^+ and NO_3^- levels across all soil types, a result that emphasizes the role of cover crop diversity in improving soil nutrient status. This reinforces the concept that a diverse cover cropping system, through its varied root structures and organic matter contributions, can create a more favorable soil environment for nutrient retention and uptake (Tonitto et al., 2006). The strong relationship between POXC and FDA underscores the interconnected nature of soil organic carbon and microbial activity. Increased POXC, indicative of higher labile carbon content, is likely to provide more substrates for microbial activity, thus increasing FDA hydrolysis rates.

This finding is crucial for understanding soil health, as it suggests that the addition of organic matter through cover crops can stimulate biological activity and improve soil quality (Poeplau & Don, 2015). Our findings elucidate the dynamic effects of cover crops on soil nitrogen levels and microbial activity over time, indicating that cover crops, especially diverse mixes, can significantly enrich soil biochemical properties. While there is a need for longer-term studies to solidify these conclusions, the evidence presented supports the inclusion of mixed cover crops as a strategy for sustainable soil management, particularly in systems were maintaining soil fertility and promoting biological activity are critical concerns.

4.4 Impact of Cover Crops on Subsequent Main Crop Growth (Corn and Pepper)

4.4.1 Pepper

The utilization of cover crops as green manure was evaluated for its impact on the growth of pepper plants in a controlled pot experiment. The experimental design assessed the influence of these green manures on subsequent pepper biomass across different soil types and over two growing seasons. A General Linear Model (GLM) highlighted the substantial effects of cover crop-derived green manure on soil characteristics and biomass yield of pepper plants ($F(16,60) = 98.05$; $P < 0.001$; Wilk's $\lambda = 0.002$; partial $\eta 2 = 0.95$). Soil type also emerged as a significant factor influencing pepper growth ($F(7,87) = 48.35$; $P < 0.001$; Wilk's $\lambda = 0.043$; partial $\eta 2 = 0.79$). The temporal aspect, denoted by year, proved to be a crucial variable ($F(7,30) = 28.30$; $P < 0.001$; Wilk's $\lambda = 0.132$; partial $\eta 2 = 0.86$). Interaction effects between year and cover crop treatment, as well as the three-way interaction involving year, cover crop, and soil type, were found to be significant ($F(14,60) = 1.12$; $P < 0.001$; Wilk's $\lambda = 0.62$; partial $\eta 2 = 0.20$ and $F(56,473) = 2.25$; $P < 0.001$; Wilk's $\lambda = 0.28$; partial $\eta 2 = 0.166$, respectively). Details of these interactions are presented in Appendices 5 and 6.

Biomass Production:

Figure 18 illustrates the biomass production of pepper plants in 2022 and 2023, cultivated in pots containing soils enriched with biomass from three different cover crop treatments. Over the two years, no statistically significant differences were observed between the cover crop treatments for either soil type. This uniformity suggests that while cover crops may improve soil properties, their residual effects as green manure on pepper plant biomass are comparable regardless of the cover crop type used.

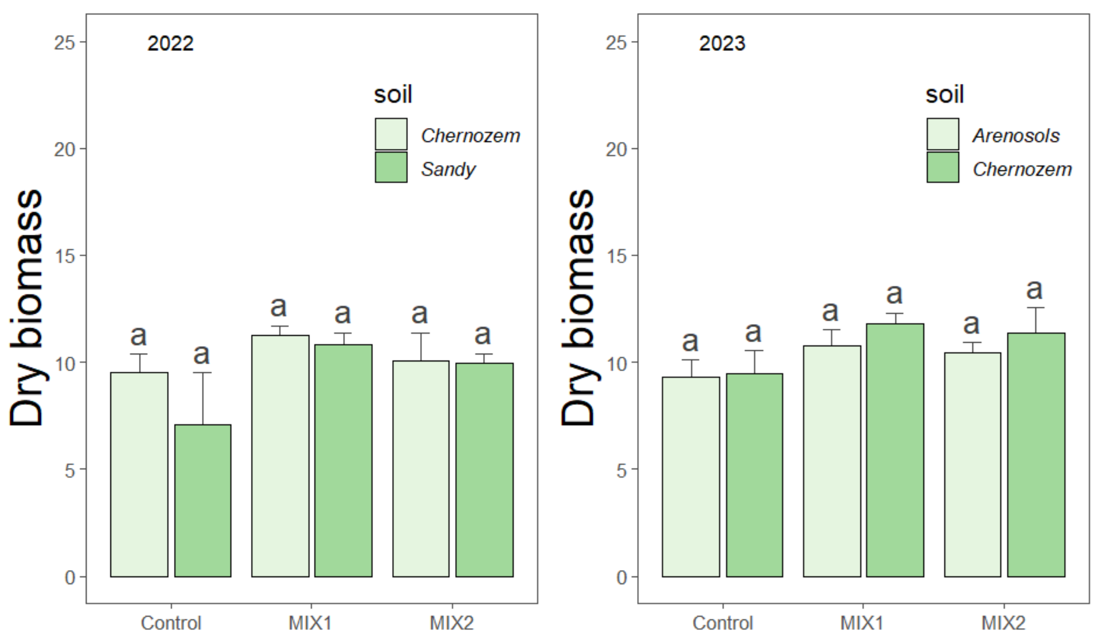

Figure 18 The effect of cover crops on biomass production on two soil types in two years for the main crop of pepper. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05)

The consistent results across different soil types and years imply that the benefits of cover crops as green manure may not be immediately discernible in terms of biomass production for pepper plants. The results may suggest that while green manure contributes to soil fertility, its immediate impact on pepper biomass might be limited or influenced by other factors such as pepper variety, soil microbial activity, or specific nutrient dynamics post-green manure decomposition. Furthermore, the lack of significant differences between cover crops may indicate that the choice of cover crop for green manure, within the range tested, does not differentially impact the subsequent pepper crop in a pot experiment context. It is also plausible that the two-year period was not sufficient to detect long-term effects, which could become more apparent in successive growing seasons.

Mycorrhizal Colonization (Myco%) and Electrical Conductivity (EC):

This section of the study examined the influence of cover crops on mycorrhizal colonization (Myco%) and soil electrical conductivity (EC) in the cultivation of pepper plants over two successive years, with a focus on discerning the effects across different soil types.

Figure 19 delineates Myco% in two distinct years. In 2022, mycorrhizal colonization was not measured, indicated as 'nd*' (not determined). However, in 2023, the assessment highlighted a lack of significant differences in Myco% among the cover crop treatments in Chernozem soils. In contrast, Arenosols showed lower Myco% in control plants, with MIX1 and MIX2 treatments not differing significantly from each other. This suggests that cover crops may play a role in supporting mycorrhizal associations in soils with low organic matter content, a factor essential for pepper plants which rely on mycorrhizal symbiosis for nutrient uptake and stress tolerance.

The EC trends observed in 2022 indicate that Chernozem soil had the lowest EC values in control plots and higher values for MIX1 and MIX2 treatments, suggesting that cover crops may influence ionic strength and nutrient solubility in the soil. Sandy soil mirrored this trend, with control plots again showing the lowest EC values and MIX2 exhibiting the highest, though not significantly different from MIX1. In 2023, a similar pattern emerged with Chernozem soil, where MIX1 and MIX2 treatments correlated with higher EC values compared to control plots. For Arenosol soil, MIX2 again presented the highest EC, while control plots had the lowest.

These results may imply that cover crops, specifically mixed cover crops, can enhance the availability of soluble salts and nutrients, possibly through the addition of organic matter and its subsequent decomposition.

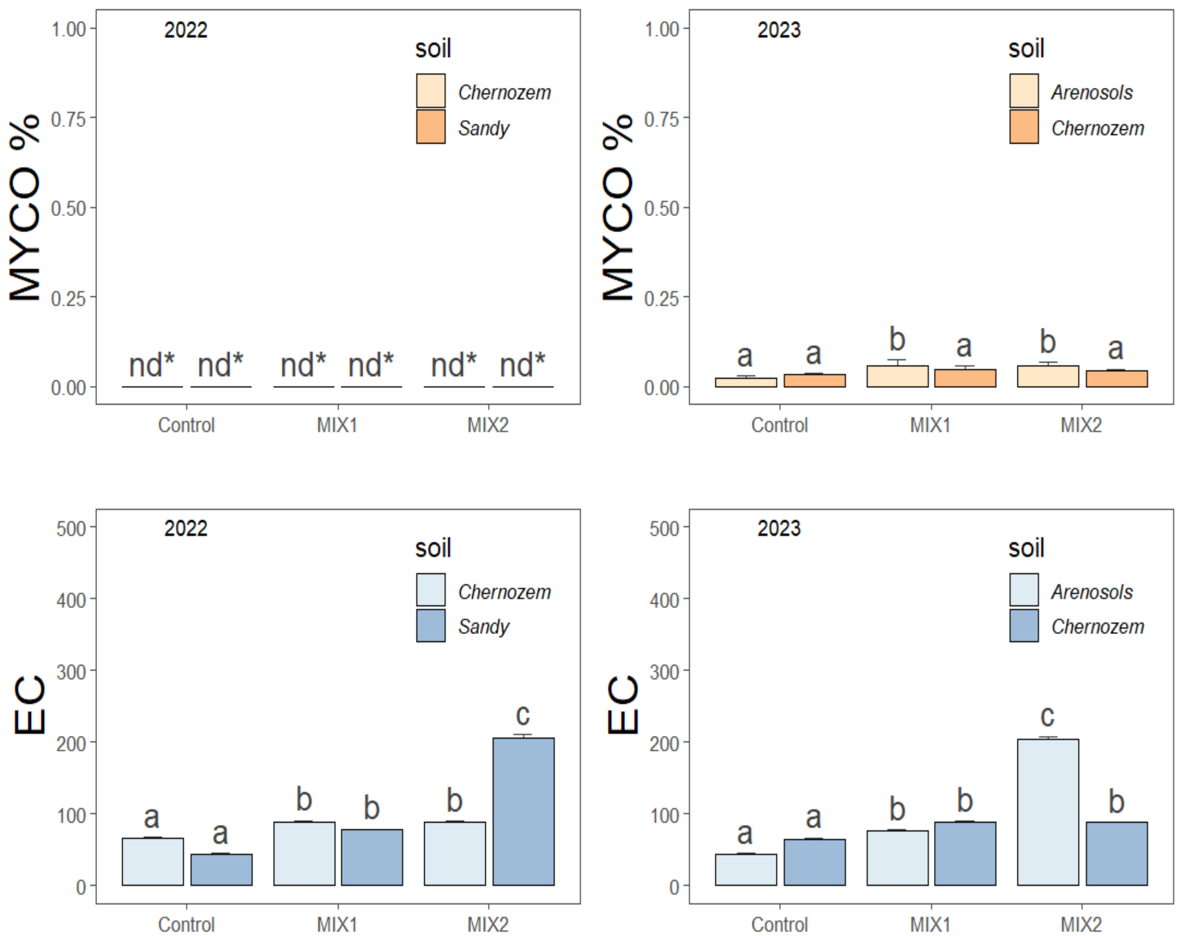

Figure 19 The effect of cover crops on Myco% and EC on different soil types in two years for the main crop of pepper. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05). (Note: values marked with nd cannot be determined)*

The absence of Myco% data in the first year highlights the importance of temporal dynamics in evaluating the impact of cover crop utilization. The findings from the second year suggest that while cover crops might not significantly alter mycorrhizal associations in Chernozem soil, they may benefit Arenosol soil by possibly improving conditions for mycorrhizal fungi establishment. The EC data across two years consistently demonstrates that the inclusion of cover crops, particularly mixed species, appears to enrich the soil's EC. This enrichment could be attributed to the increased decomposition of organic matter, leading to a release of nutrients and enhanced soil fertility, particularly in soils like Aerosols which are typically low in nutrients and organic matter. The two-year comparative analysis provides insight into the role of cover crops as green manure in influencing soil biological and chemical properties. While the effect on mycorrhizal colonization was not significant in Chernozem soil, potential benefits in Arenosols were noted. EC measurements indicate a positive influence of cover crops on soil nutrient availability, which can be crucial for the main crop's growth and productivity. These findings support the use of cover crops as a strategy to improve soil health and function in pepper cultivation. It also underscores the need for a multi-year approach to fully understand the implications of cover cropping systems on subsequent main crops.

Permanganate Oxidizable Carbon and Fluorescein Diacetate Hydrolysis:

Assessment of Cover Crop-Derived Green Manure Effects on Permanganate Oxidizable Carbon and Enzyme Activity in Soils for Pepper Cultivation: In a controlled pot experiment conducted over two years, the impacts of green manure derived from cover crops on soil properties, specifically Permanganate Oxidizable Carbon (POXC) and Fluorescein Diacetate (FDA) hydrolysis, were evaluated to ascertain their influence on pepper plant growth.

In 2022, within Chernozem soil, the control treatment displayed significantly lower POXC levels compared to the MIX1 and MIX2 treatments, suggesting that the application of green manure enriches the labile carbon pool, which is crucial for soil health and crop productivity. Interestingly, MIX1 and MIX2 treatments demonstrated comparable POXC levels, indicating a threshold of benefit in terms of carbon input from these cover crops. In contrast, Sandy soil exhibited a clear hierarchy, with MIX2 treatment achieving higher POXC than MIX1, indicating differential responses of these soils to cover crop treatments. By 2023, the trend in Arenosols was similar to the previous year's observations in Chernozem and Sandy soils, with both MIX1 and MIX2 treatments showing a notable improvement in POXC levels over the control. Chernozem soil maintained this trend, with MIX2 again surpassing MIX1 in enhancing POXC, suggesting sustained soil improvement over time.

FDA In 2022, FDA hydrolysis patterns across soils mimicked those observed for POXC, with the control treatment in Chernozem and Sandy soils showing lower enzyme activity, indicative of a less active soil microbiome. MIX1 and MIX2 did not significantly differ, which could imply that the level of microbial stimulation provided by the cover crops reached a plateau. In 2023, similar results were observed. Arenosols soil echoed the patterns seen in Chernozem soil from the previous year, with MIX1 and MIX2 significantly boosting FDA hydrolysis compared to the control, affirming the role of green manure in fostering microbial activity. In Chernozem soil, FDA hydrolysis levels were substantially higher in MIX1 and MIX2 treatments than the control, though no significant differences were noted between the two mix treatments.

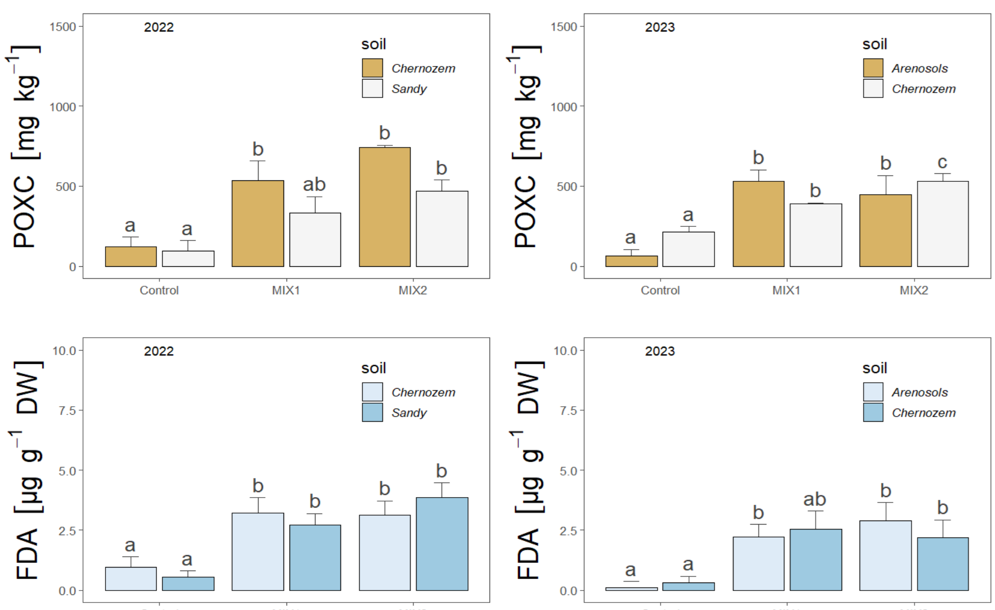

Figure 20 The effect of cover crops on POXC and FDA on different soil types in two years for the main crop of pepper. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The consistency of POXC and FDA results over two years suggests a reliable effect of cover crop-derived green manure on both soil carbon availability and microbial activity. MIX2's repeated superior performance in POXC enhancement points towards its effective composition for soil amendment, especially in soils with different inherent fertilities.

FDA hydrolysis activity being consistently lower in control treatments across both years and soil types reaffirms the importance of cover crops in maintaining an active soil biota, which is essential for the biogeochemical cycling of nutrients and overall soil health. The lack of significant differences between MIX1 and MIX2 treatments in most cases could be attributed to the similarity in the quality or decomposability of organic matter they provide, which may have reached a point of diminishing returns regarding microbial stimulation and labile carbon provision.

Nitrogen Status (NH_4^+, NO_3^-, N_{min}):

Analysis of Nitrogen Status in Soils Post-Cover Crop Incorporation for Pepper Cultivation: To discern the impact of cover crop-derived green manure on the soil nitrogen status as indicated by ammonium (NH_4^+), nitrate (NO_3^-), and total mineral nitrogen (N_{min}) values for two years across varied soil types and their effects on subsequent pepper plant growth.

(NH_4^+) Values The 2022 data revealed a significant increase in NH_4^+ levels in Chernozem soil with MIX1 and MIX2 treatments as compared to the control ($P < 0.05$). Notably, MIX2 outperformed MIX1 ($P < 0.05$), indicating its potential for greater nitrogen provision. A similar pattern emerged in Sandy soil, where MIX2 also led to higher NH_4^+ concentrations than MIX1.

In 2023, Arenosols and Chernozem soils showed that control treatment lagged behind MIX1 and MIX2, with no discernible differences between the two mix treatments. This consistency across years and soil types underscores the potential of cover crop mixes to enhance soil NH_4 content, an essential nutrient for pepper growth.

(NO_3^-) Values for NO_3^- in 2022, both cover crop mixes significantly increased NO_3^- levels in Chernozem soil over the control, while MIX2 again demonstrated a superior capacity to elevate NO_3^- in Sandy soil compared to MIX1. The trend continued into 2023, where in Arenosols and Chernozem soils, MIX2 consistently showed higher NO_3^- values than MIX1, confirming the effectiveness of MIX2 in boosting available soil nitrogen.

(N_{min}) N_{min} trends followed NO_3^- closely, with MIX2 often leading to higher levels, indicating a robust contribution to the overall mineralizable nitrogen pool in the soil. These increases are crucial for the nitrogen-demanding pepper plants, potentially leading to better growth and yields.

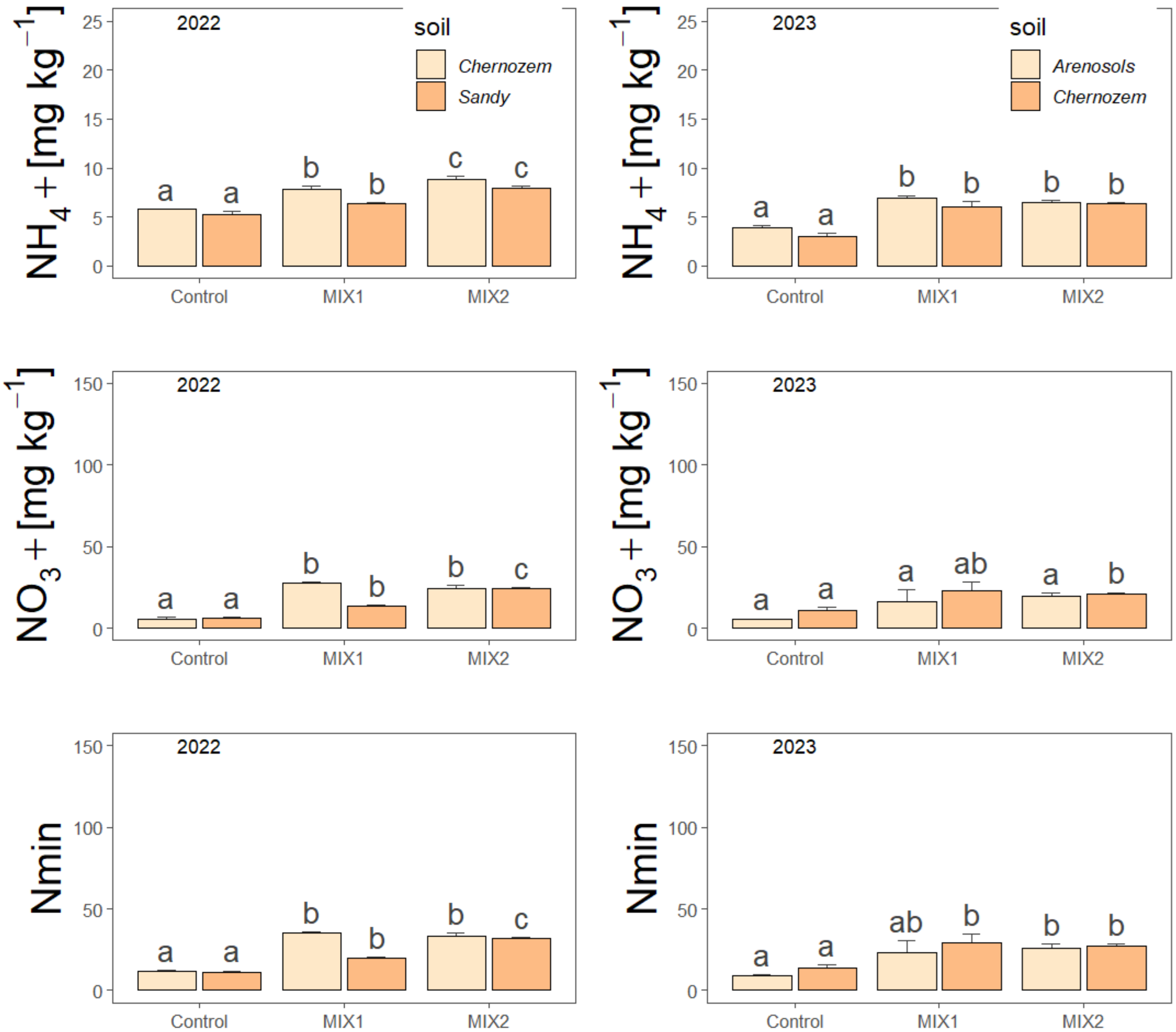

Figure 21 The effect of cover crops on nitrogen status on different soil types in two years for the main crop of pepper. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The repeated higher nitrogen values associated with MIX2 across both years and soils suggest a strong influence of cover crop composition on nitrogen cycling and availability. MIX2's composition, possibly including leguminous plants, could be providing a greater amount of nitrogen through fixation and subsequent mineralization upon decomposition. This effect is essential for supporting the nutrient needs of subsequent crops like pepper. The consistency in nitrogen enhancement by cover crop treatments and its absence in control plots is a strong endorsement for the incorporation of cover crops into crop rotation plans.

However, the similarity in results between MIX1 and MIX2 in some cases could point to a saturation effect where the maximum benefit of nitrogenous input from cover crops is reached. Particularly diverse mixes have been shown to positively affect soil nitrogen status, which translates to potential benefits for the main crop's growth. While the control plots consistently showed lower nitrogen values, indicating the need for additional nutrient inputs, the use of cover crops as green manure presents a sustainable alternative to improve soil fertility and support crop production systems.

In *Figure 22*, the correlation matrix based on Pearson's correlation coefficient presents the relationships between various soil parameters across two years. A strong positive correlation (r = 0.7) between NH_4^+ and NO_3^- indicates that increases in NH_4 levels are closely associated with increases in NO_3 levels within the soil. This relationship is likely reflective of the nitrification process where NH_4 is oxidized to form NO_3^-, a crucial step in the nitrogen cycle that facilitates plant-available nitrogen. The relationship between NH_4^+ levels and POXC (Permanganate Oxidizable Carbon), also showing a strong correlation (r = 0.7), suggests that the presence of easily oxidizable carbon is aligned with higher NH_4 content. This may be due to the decomposition of organic matter, where the mineralization process converts organic nitrogen into NH_4.

The correlation between NH_4^+ levels and FDA (Fluorescein Diacetate) hydrolysis activity (r = 0.7) suggests that areas with higher levels of NH_4 also exhibit increased microbial activity, given that FDA hydrolysis is a commonly used indicator of microbial enzyme activity. There is a medium positive correlation (r = 0.6) between NO_3^- and POXC, indicating a moderate association between NO_3 content and the amount of labile organic carbon, potentially pointing to the integral role that organic matter plays in providing a substrate for microbial processes leading to nitrification. Additionally, the positive correlation (r = 0.6) between NO_3^- and FDA suggests that higher levels of NO_3 are generally in tandem with heightened microbial activity, which could have implications for nutrient cycling and availability in the soil.

The medium positive correlation (r = 0.5) between POXC and FDA implies that as the amount of labile organic carbon increases, there is a corresponding increase in microbial activity, affirming the importance of organic carbon as a driver for microbial processes.

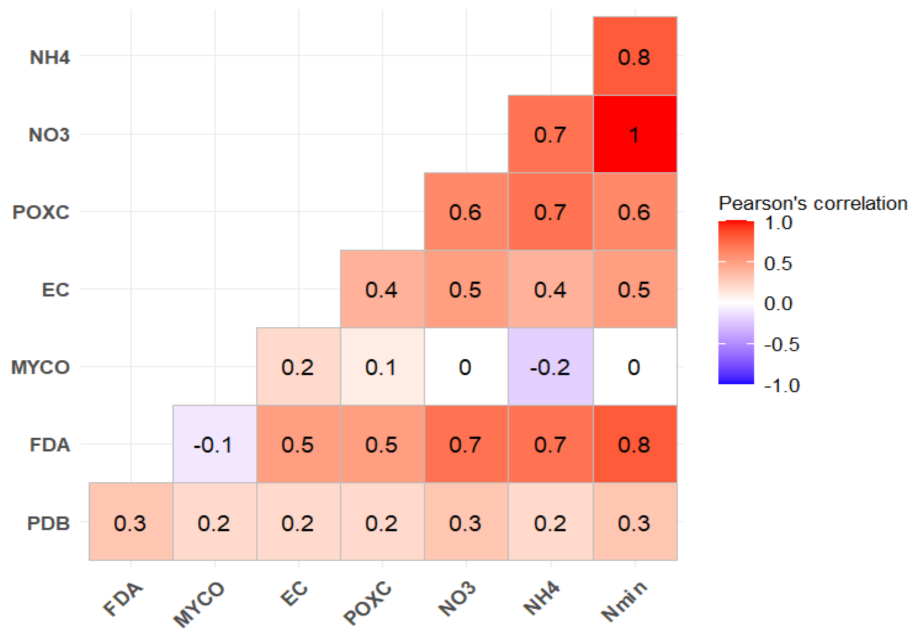

Figure 22 Pearson's correlation matrix between soil parameters for the main crop of pepper. Correlations are shown in blue (positive) and red (negative); the intensity of the color is proportional to the correlation coefficient.

These correlations provide valuable insights into the complex interplay between soil chemistry and biology. They underscore the interconnectedness of soil nutrients, organic matter, and microbial activity. The strong correlations involving NH_4^+, NO_3^-, and FDA activity emphasize the significant role of microbial processes in nutrient transformation and availability in soils, which are essential for plant growth and ecosystem sustainability.

4.4.2 Maize

The impact of green manure from different cover crops on the growth of corn plants was evaluated in a pot experiment that spanned two years, examining soil characteristics and biomass production across three types of soil.

A General Linear Model (GLM) analysis revealed that cover crops significantly influenced the soil properties and subsequent biomass production in corn ($F(35,280) = 40.83$; $P < 0.001$; partial $\eta 2 = 0.78$). Soil type also demonstrated a significant impact ($F(21,190) = 51.31$; $P < 0.001$; partial $\eta 2 = 0.83$), as did the year of study ($F(7,66) = 102.97$; $P < 0.001$; partial $\eta 2 = 0.91$). Interaction effects between the year and cover crop, soil type, and a three-way interaction involving the year, cover crop, and soil type were significant, indicating complex interdependencies between these factors and their collective influence on corn biomass production.

Biomass production patterns:

In *Figure 23,* biomass production varied across soil types and between the two years studied. In 2022, Chernozem soil showed no significant difference in biomass production between the broad bean and Mustard treatments, while the Oat treatment yielded a significantly lower biomass. Luvisol soil presented no major difference between Control and Oat treatments, but broad bean treatment displayed lower biomass compared to MIX1 and MIX2. Sandy soil results followed a similar pattern to Chernozem, with Oat treatment underperforming compared to Broad bean and Mustard. The year 2023 continued to show the influence of soil type on biomass production. Arenosols soil highlighted the broad bean treatment's higher productivity over Mustard and Oat. In Chernozem, the broad bean treatment once again outperformed Mustard and Oat. Luvisol soil's results from 2022 were repeated, with no significant differences between the Control and Mustard treatments, while MIX1 and MIX2 exceeded others in biomass production.

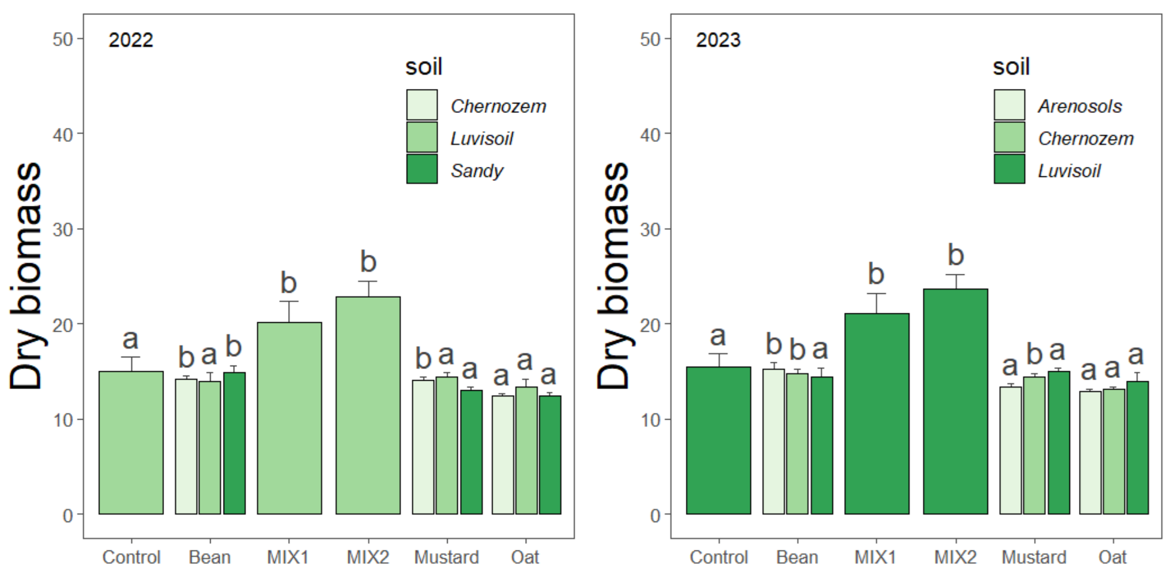

Figure 23 The effect of cover crops on biomass production on two soil types in two years for the main crop of corn. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The data indicate that cover crops, particularly mixed ones, contribute positively to biomass production, potentially through improved soil health and nutrient availability. The consistently higher performance of MIX1 and MIX2 treatments in biomass production across soil types suggests these cover crop combinations may be providing a more balanced nutrient release or fostering more favorable soil microbial environments conducive to corn growth. The absence of significant differences between Broad bean and Mustard treatments in Chernozem soil could imply that these cover crops similarly contribute to soil fertility in rich, loamy soils. However, the comparatively lower performance of the Oat treatment across soil types suggests that not all cover crops contribute equally to biomass production, which could be due to differences in their growth patterns, root architecture, or nutrient cycling.

Mycorrhizal Colonization (Myco%) and Electrical Conductivity (EC):

Influence of Green Manure from Cover Crops on Mycorrhizal Colonization and Electrical Conductivity in Corn Cultivation: The study explored the effects of green manure from cover crops on mycorrhizal colonization (Myco%) and electrical conductivity (EC) in the soil for corn plants over two consecutive years.

Myco% In 2022, Chernozem soil exhibited no significant variation in Myco% across the treatments. In contrast, Luvisol soil presented a notable response to MIX1 treatment, which demonstrated a higher Myco% compared to other treatments, highlighting the potential of specific cover crops to enhance mycorrhizal associations. Interestingly, Sandy soil reported a higher Myco% in the Oat treatment compared to Broad bean and Mustard.

The year 2023 saw no major distinctions in mycorrhizal colonization between Mustard and Oat treatments in Arenosols. However, the Broad bean treatment indicated a decrease in Myco% in comparison with Mustard and Oat treatments in this soil type. In Chernozem, Broad bean treatment led to a significant increase in Myco%, suggesting that broad bean plants may foster a more favorable environment for mycorrhizal fungi. Luvisol's results were less definitive, with MIX1 standing out against control but no significant difference between the other treatments.

EC The 2022 EC values for Chernozem soil revealed a substantial distinction between Mustard and Oat treatments, with the Broad bean treatment showing a higher average EC. For Luvisol soil, significant differences were found between Control and Mustard treatments, while MIX2 had a notably lower EC compared to others.

In Sandy soil, marked differences between Mustard and Oat treatments were observed. In 2023, Arenosols exhibited significant differences in EC values between Mustard and Oat treatments, with the Broad bean treatment displaying higher EC, suggesting variations in soil salinity and nutrient solubility influenced by cover crop management.

Chernozem and Luvisol soils showed trends similar to the previous year, where Broad bean treatment and MIX1 exhibited higher EC, while MIX2 was lower in comparison to the others.

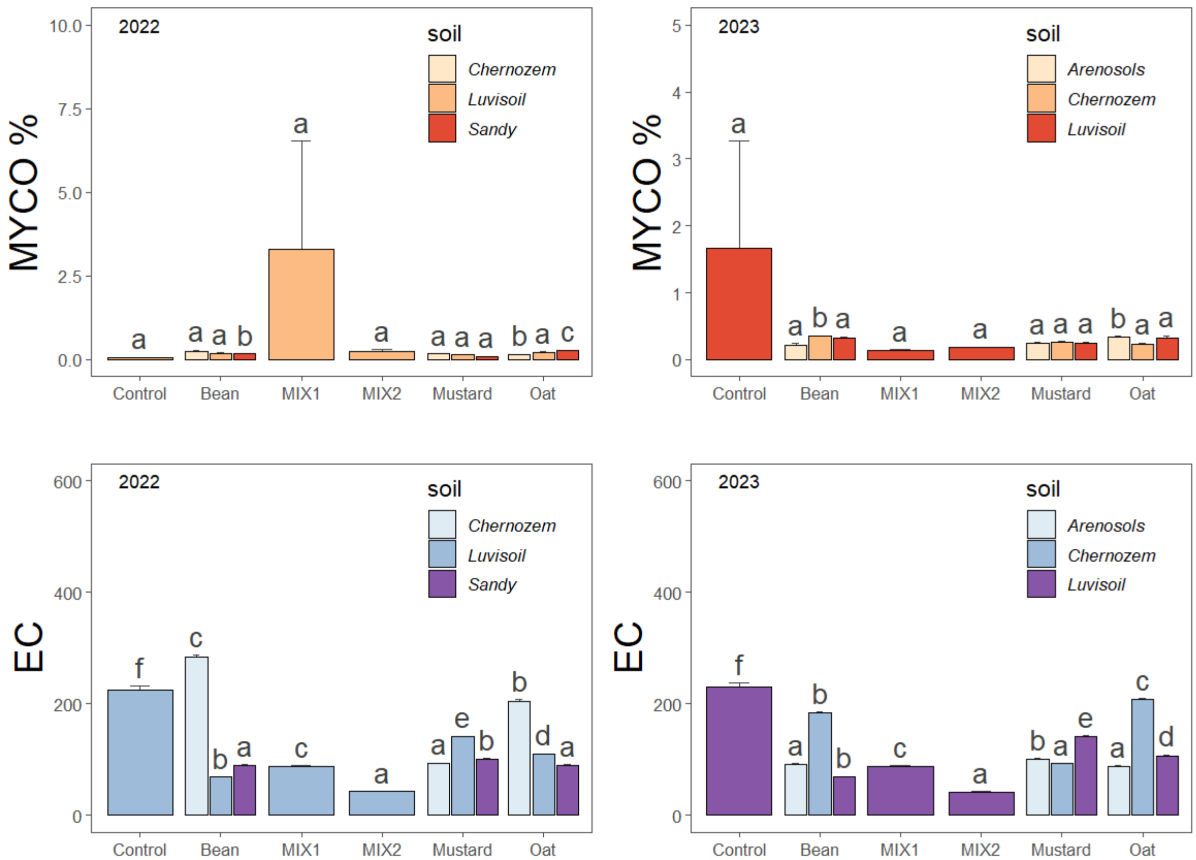

Figure 24 The effect of cover crops on Myco% and EC on different soil types in two years for the main crop of corn. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The data from both years present a complex interaction between cover crop type, soil properties, and their combined effect on mycorrhizal colonization and soil EC. The varying impact on Myco% suggests that cover crop choice can significantly influence mycorrhizal symbiosis, which is essential for nutrient uptake in corn. The EC findings indicate that cover crops might affect nutrient availability and ion exchange in the soil, which can impact plant growth and development. The contrast in effects between soil types and years emphasizes the dynamic nature of agricultural ecosystems and the necessity for adaptable management practices. The significant variations in Myco% and EC, particularly in response to the Broad bean and MIX1 treatments, underline the potential benefits of using specific cover crops to optimize conditions for subsequent main crop cultivation.

Analysis of the Impact of Cover Crop Green Manure on Soil Permanganate Oxidizable Carbon (POXC) and Fluorescein Diacetate Hydrolysis (FDA) in Corn Production:

We evaluate how green manure derived from various cover crops influences soil properties, specifically the levels of permanganate oxidizable carbon (POXC) and enzyme activity as indicated by fluorescein diacetate (FDA) hydrolysis in different soil types over two growing seasons for corn.

POXC In 2022, the POXC values varied significantly among treatments, highlighting the influence of cover crops on labile carbon content in the soil. For Chernozem and Luvisol soils, the Broad bean treatment demonstrated higher POXC values than Oat and Mustard treatments. The MIX2 treatment showed notably higher POXC values than other treatments, suggesting its potential as a robust source of labile carbon, which is crucial for soil health and crop productivity. In Sandy soil, the Broad bean treatment presented higher POXC compared to Mustard and Oat, aligning with the observed trends in other soil types. In 2023, Arenosols soil exhibited significant differences in POXC between Broad bean and Mustard treatments and between Broad bean and Oat treatments. Chernozem soil also displayed significant differences between Broad bean and Mustard and Broad bean and Oat treatments. Similarly, Luvisol soil showed variations between Control and Broad bean treatments and between Broad bean and MIX1 and MIX1 and MIX2 treatments, with Broad bean demonstrating notably higher POXC values.

FDA Regarding FDA activity, in 2022, the Broad bean treatment in Chernozem and Luvisol soils showed significantly higher activity than Control, MIX1, Mustard, and Oat treatments, which aligns with the enhanced POXC values and suggests a correlation between organic matter content and microbial activity. On Sandy soil, Broad bean again displayed higher FDA activity than Mustard and Oat treatments. In 2023, trends in FDA activity mirrored those from 2022, with the Broad bean treatment showing significantly higher activity in Arenosols, Chernozem, and Luvisol soils. This consistency reinforces the premise that Broad bean green manure contributes positively to microbial activity across soil types. MIX2 also exhibited higher FDA activity in Luvisol soil, indicating its potential to stimulate soil biology.

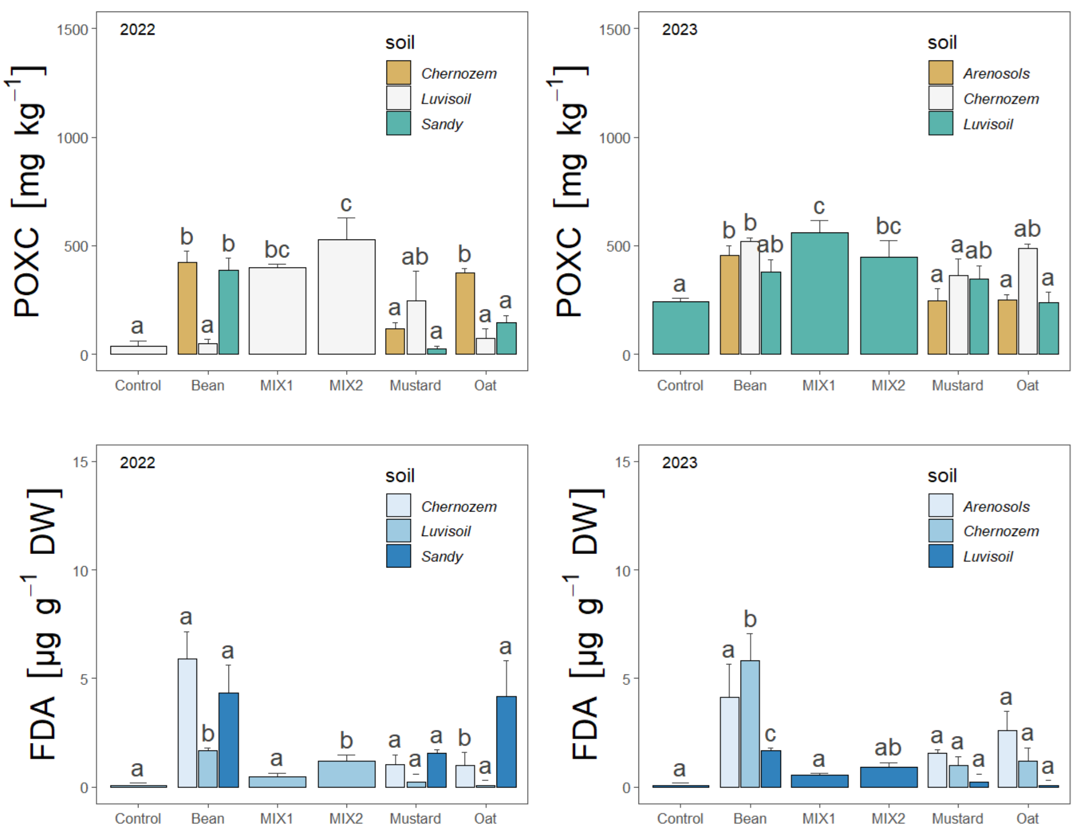

Figure 25 The effect of cover crops on POXC and FDA on different soil types in two years for the main crop of corn. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The results from both years provide insight into the dynamic relationship between cover crop green manure and soil health parameters. The consistently higher POXC and FDA values in plots treated with Broad bean and MIX2 green manure indicate that these cover crops significantly enhance both the quantity of labile carbon and microbial activity in the soil, which are vital components for sustaining soil fertility and promoting healthy crop growth.

The data suggests that the use of specific cover crops as green manure can result in improved soil conditions that favor higher levels of microbial enzymatic activity and potentially greater availability of nutrients for the corn plants. These findings have implications for the management of soil health in agricultural systems, where enhancing the function and resilience of soil through organic amendments is becoming increasingly important.

Nitrogen Status (NH_4^+, NO_3^-, N_{min}):

NH_4^+ The 2022 data show a trend where cover crops, especially Broad bean, MIX1, and MIX2, contribute to significantly higher NH_4^+ concentrations compared to Control and Mustard treatments in Luvisol soil, with Broad bean also surpassing Oat. This pattern suggests that certain cover crops can improve nitrogen availability in the form of NH_4^+. In contrast, Sandy soil saw the Broad bean treatment excel over Mustard and Oat treatments.

For 2023, Arenosols did not demonstrate significant differences in NH_4^+ among Broad bean, Mustard, and Oat treatments, whereas Chernozem soil showed Broad bean treatment to have a significant increase over Mustard, and Luvisol soil had Broad bean exceed Control, MIX1, and MIX2 in NH_4+ levels.

NO_3^- In 2022, the NO_3^- values on Chernozem soil placed Broad bean treatment ahead of Mustard and Oat, whereas MIX1 and Oat treatments led on Luvisol soil. On Sandy soil, Oat outperformed Mustard, indicating varied responses of cover crops to soil types in NO_3 provision.

The following year, Arenosols soil results paralleled the previous year's Chernozem findings, with Broad bean showing higher NO_3^- values than Mustard and Oat. Similarly, on Luvisol soil, Broad bean, MIX2, and Oat treatments significantly outperformed Control and Mustard, with Broad bean also leading over MIX1.

N_{min} The 2022 N_{min} data for Chernozem soil underscore Broad bean's higher values compared to Mustard, with Luvisol soil presenting a similar pattern. Sandy soil reflected this trend, with Broad bean and Oat surpassing Mustard in N_{min} content.

In 2023, Arenosols soil highlighted the Broad bean treatment's superior N_{min} values compared to Mustard and Oat, while in Chernozem soil, Broad bean again surpassed Mustard. On Luvisol soil, Broad bean treatment marked higher N_{min} levels than Mustard and MIX1, with Oat also topping Mustard all showed in *Figure 26.*

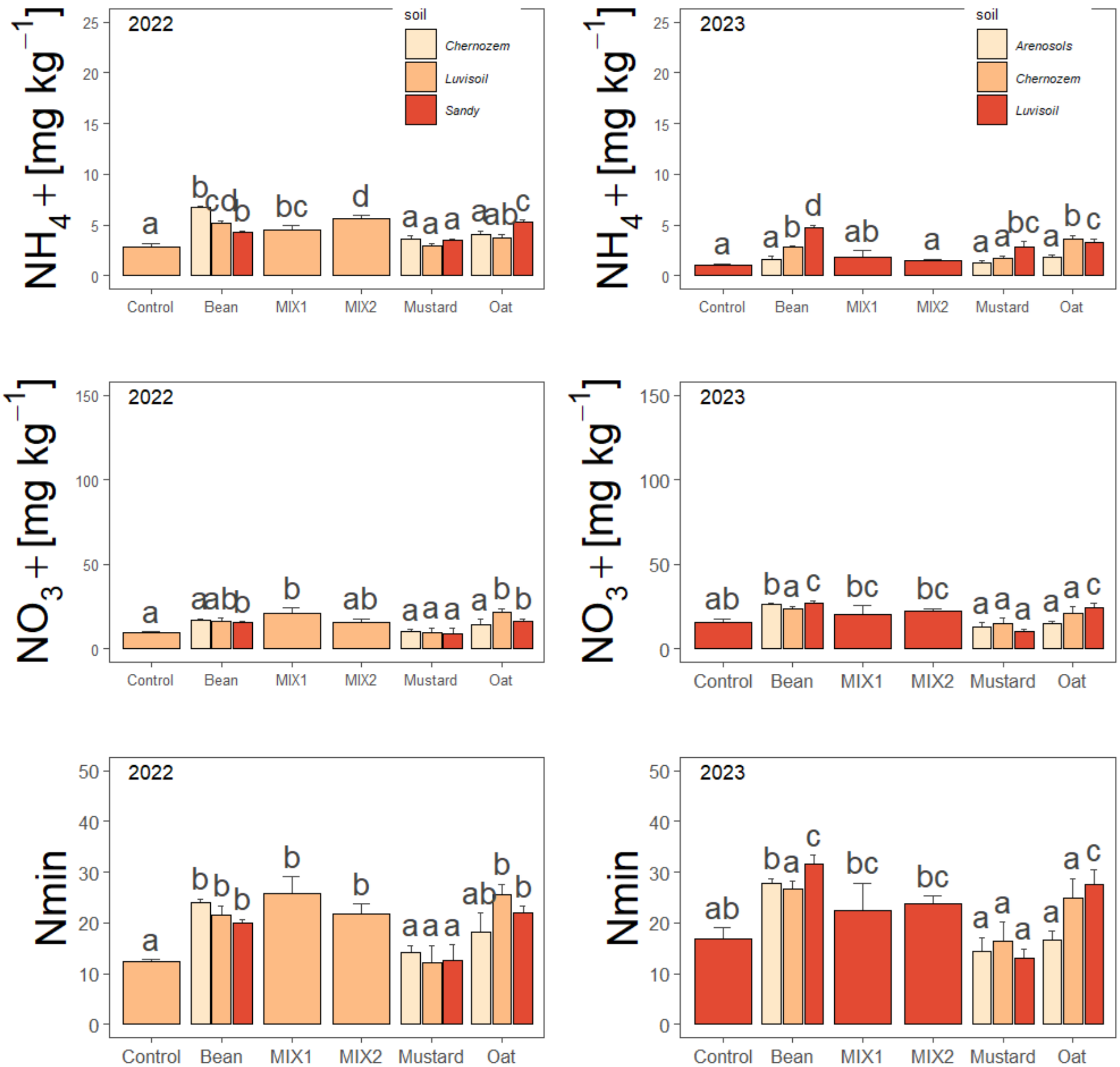

Figure 26 The effect of cover crops on nitrogen status on different soil types in two years for the main crop of corn. Results of the multiple comparisons of the GLM model are indicated by the letters above the graph. Statistical significance was determined using Duncan post-hoc test (P<0.05).

The observed increases in NH_4^+, NO_3^-, and N_{min} concentrations across various soil types and years underscore the ability of specific cover crops to enhance nitrogen availability in soils, a critical factor for the growth and yield of corn. The consistent performance of the Broad bean treatment across different soils and years suggests its potential as a green manure crop to improve nitrogen cycling and soil fertility. Furthermore, the differences in nitrogen status responses to MIX1 and MIX2 treatments indicate the complexity of soil-cover crop interactions and the importance of selecting the right cover crop mix to optimize nutrient dynamics.

Figure 27 presents a correlation matrix for various soil parameters measured in a study on the main crop of maize (corn). Here's an interpretation of the results based on the Pearson correlation coefficients provided: NH_4^+ and NO_3^-: The correlation coefficient ($r = 0.1$) indicates a very weak positive correlation, suggesting that there is little to no linear relationship between (NH_4^+) and (NO_3^-) concentrations in the context of this study.

NH_4^+ and POXC: With a correlation coefficient (r = 0.0), there is no observed correlation between NH_4^+ levels and permanganate oxidizable carbon (POXC). This indicates that the labile organic carbon measured by POXC is not directly linked to the NH_4 content in these maize crops.

NH_4^+ and FDA: A weak positive correlation (r = 0.2) suggests that there is a slight association where increases in NH_4^+ might be associated with increases in fluorescein diacetate (FDA) hydrolysis activity, a measure of microbial activity.

NO_3^- and POXC: The medium positive correlation (r = 0.4) between NO_3 and POXC suggests a moderate relationship, indicating that higher NO_3 levels might be associated with increased oxidizable organic carbon content, possibly due to enhanced microbial processing of organic matter leading to nitrification.

NO_3^- and FDA: A weak positive correlation (r = 0.2) indicates that higher NO_3 levels are slightly associated with increased microbial activity, as evidenced by FDA hydrolysis.

POXC and FDA: Similarly, a weak positive correlation (r = 0.2) between POXC and FDA activity indicates a slight association where soils with higher levels of labile organic carbon may experience slightly more microbial activity.

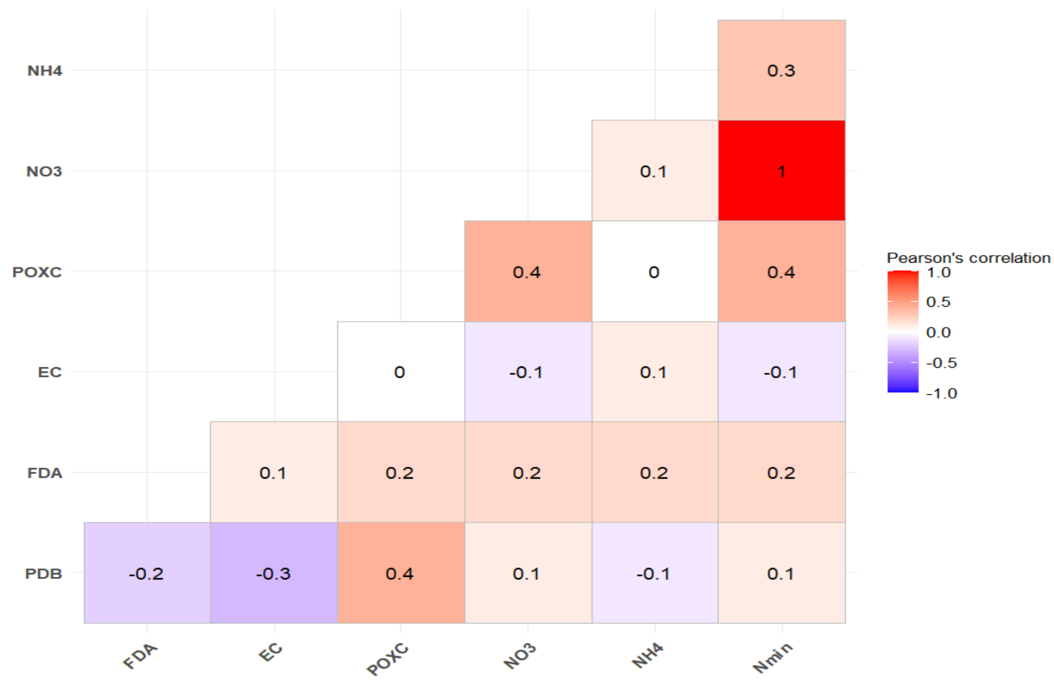

Figure 27 Pearson's correlation matrix between soil parameters for the main crop of Corn. Correlations are shown in blue (negative) and red (positive); the intensity of the color is proportional to the correlation coefficient.

The correlations presented in this matrix suggest that the relationships between nitrogen forms, labile carbon, and microbial activity in this study are generally weak. This could be due to a variety of factors, including differences in the timing of nitrogen and carbon availability, variations in microbial communities, or other environmental and management factors not captured by this analysis. In agricultural practice, these findings could imply that enhancing one soil parameter does not necessarily lead to expected changes in another, highlighting the complexity of soil ecosystems. For instance, adding green manure may increase organic carbon (POXC) but does not automatically translate to higher available nitrogen (NH_4^+ or NO_3^-) or vice versa. Therefore, integrated soil management approaches are needed to balance these factors for optimal plant growth and soil health.

4.4.3 Soil Type Responses to Cover Crop Applications

Comparison of three soils by physical-chemical characteristics:

The three soil types Arenosols, Chernozems, and Luvisols exhibited distinct responses to cover crop treatments, reflecting their inherent physical-chemical differences (refer to Table 5 in Materials and Methods for soil characteristics). Arenosols, with their sandy texture and low initial organic matter content (1.16%), generally showed lower baseline values for most parameters compared to the other two soil types. However, these soils demonstrated a considerable capacity for improvement with cover cropping, particularly in terms of POXC and FDA activity (see Figures 20 and 25).

Chernozems, characterized by their loamy texture, high organic matter content (2.81%), and near-neutral pH, generally exhibited higher baseline values for nutrient availability and microbial activity. These soils showed consistent positive responses to cover crop treatments, particularly with the Broad bean and MIX treatments, across most measured parameters (see Figures 16-25).

Luvisols, with their clay-loam texture, moderate organic matter content (1.64%), and slightly acidic pH, displayed a high water-holding capacity. The response to cover crops in Luvisols was often characterized by significant increases in POXC and FDA activity (see Figures 20 and 25), and improvements in nitrogen status, particularly with the MIX treatments (see Figures 21 and 26).

The differences in EC values across soil types (Figures 19 and 24) likely reflect the varying capacities of these soils to retain and release soluble salts, influenced by their texture and organic matter content. Soil responses to cover crops were dependent on initial conditions and inherent soil characteristics. For instance, Chernozems exhibited the highest increase in POXC and microbial activity, whereas Arenosols responded with significant gains in EC and nutrient retention. Luvisols, with their balanced water and nutrient holding capacities, showed stable improvements across all parameters.

Soil biological indicators for assessing CC application

Soil biological indicators: Fluorescein Diacetate (FDA) hydrolysis, Mycorrhizal Colonization (Myco%), and Permanganate Oxidizable Carbon (POXC):

Consistently demonstrated the positive impacts of cover cropping on soil health across all three soil types. FDA hydrolysis activity, a proxy for overall microbial activity, generally increased in response to cover crop treatments, particularly with the Broad bean and MIX treatments (see Figures 20 and 25). This suggests an enhancement in microbial biomass and enzyme activity, crucial for nutrient cycling and organic matter decomposition.

Mycorrhizal colonization (Myco%), although variable across soil types and years, also tended to be higher in cover-cropped treatments compared to controls, especially in the Broad bean, MIX1, and MIX2 treatments (see Figures 19 and 24). This highlights the potential of cover crops to foster beneficial plant-fungal symbiotic relationships, which are essential for nutrient uptake, particularly phosphorus. POXC, a measure of labile carbon, consistently increased with cover crop treatments, most notably with the Broad bean and MIX2 treatments (see Figures 15 and 20).

This indicates an improvement in the readily decomposable fraction of soil organic matter, which serves as a food source for microorganisms and contributes to soil fertility. The consistent positive responses of these biological indicators across different soil types provide strong evidence for the broad applicability of cover cropping as a soil health management strategy.

Table 8. Comparative Table: Soil × Cover Crop × Crop Response.

Soil Type	Texture	SOM (%)	Water Holding Capacity	Best Per-forming CCs	Corn Res-ponse	Pepper Res-ponse	Micro-bial Boost (FDA, Myco%)	Mana-gement Recomme ndation	Future Research Needs
Arenosols	Sandy	1.16	Low	Broad bean, MIX	Moderate growth; best after Broad bean	Better roots in MIX2	Strong increase with Broad bean	Early CC termination to conserve water	Measure infiltration, drought resilience
Cher-nozems	Loamy	2.81	Moderate	Broad bean, MIX	Strong vegetative growth; best after MIX	Best fruit quality in MIX1	Highest overall microbial activity	Use diverse mixes to sustain fertility	Track long-term enzyme activity and C cycling
Luvisols	Clay-loam	1.64	High	MIX	High nutrient uptake; stable yield	Improved establish ment in MIX2	High POXC, Myco% in MIX	Deep-rooted legumes for compactio n relief	Phosphorus bioavailability , fungal profiling

5. NEW SCIENTIFIC RESULTS

Thesis 1 (answering Hypothesis 1):

Our research demonstrates that cover crop (CC) treatments, especially legume-based and mixed-species (MIX2)—resulted in significantly higher biomass production compared to the control (bare soil). MIX2 produced 30–40% more aboveground and root biomass, depending on soil type and year. This increase is linked to the presence of double symbiont CC interacting with beneficial microsymbionts (rhizobia and mycorrhizae), enhancing nutrient uptake, soil health and soil fertility. These findings confirm the potential of symbiont-rich CC in boosting organic inputs and supporting sustainable agriculture.

(Kabalan et al., 2022).

Thesis 2 (answering Hypothesis 2):

Cover crops, especially legume and mixed-species treatments, significantly enhanced microbial activity in low-quality Arenosol soil, as indicated by the FDA hydrolysis values, in comparison with non-leguminous CC species. In MIX2 treatments, FDA values increased by up to 35% and Myco% by 25–30% compared to control, based on statistically significant differences ($p < 0.05$), highlighting species-specific effects on biological activation. These findings confirm the importance of proper application of soil-biological tools in investigating symbiosis and microbial activities when selecting the most appropriate CC species and performance on soil-quality.

(Kabalan et al., 2023)

Thesis 3 (answering Hypothesis 3):

The use of symbiotic cover crops such as legumes *Lens culinaris* (lentil) produced the highest dry biomass among all cover crops in the field experiment ($P < 0.05$), followed by the mixed treatment (including variable plant species), that was identical result with the pot-experiment. This fact highlights lentil's effective adaptation to Mediterranean conditions and its role in food production. CC-mixture in lentil treatments led to the highest NO_3^-, NH_4^+, and total N_{min} concentrations ($P < 0.05$), underscoring their superior nitrogen-enriching effects via biological nitrogen fixation. The benefits of symbionts were performed independently from the soil-climatic conditions both in laboratory- and in field experiments.

(Prettl et al., 2024)

Thesis 4 (answering Hypothesis 4):

Soils responded differently to cover crop applications, with variations in physical-chemical- and soil-biological parameters depending on soil type, confirming the need for site-specific CC strategies. Considering the soil characteristics, the role of organic-matter content, measured by POXC and the nitrogen availability in soils can be highlighted. Soil-biological activity (FDA) and symbiotic efficiency measured by Myco% of leguminous crops, are effective tools in assessing CC-soil-crop interactions. The importance of predicting soil quality parameters are highlighted, that should be incorporated into future CC design frameworks.

(Tóth et al. 2024)

Thesis 5 (answering Hypothesis 5):

Cover crop treatments had a positive residual effect on the biomass production of main crops (pepper and maize) which was significantly higher in soils treated with legumes and mixtures in particular, MIX2 and legume-based treatments led to a 10–18% increase in main crop biomass compared to the control. The improved biological parameters under CC traetments (FDA, Myco%, POXC) translated to enhanced biomass and yield in subsequent crops, investigated both laboratory and field-conditions Pepper for instance planted in MIX-treated Luvisol showed a notable increase in total biomass and chlorophyll content compared to the control. These results underscore the link between soil microbial health and main crop productivity.

(Kabalan et al. 2024).

6. CONCLUSION AND RECOMMENDATION

This research investigated the multifaceted role of cover crops in enhancing soil fertility and agricultural productivity across different soil types, environmental conditions, and cropping systems. Through a comprehensive series of controlled pot and field experiments, this research demonstrated that strategic cover crop management, particularly with leguminous species and well-designed mixtures (MIX1 and MIX2), yields significant improvements in soil nutrient status (NH_4^+, NO_3^-, and N_{min}), elevates soil biological activity (FDA), and increased labile soil organic matter (POXC). While the residual benefits for subsequent main crops were crop-specific with maize biomass showing a more consistent positive response than pepper the overall findings confirm that cover cropping is a cornerstone of sustainable agriculture. The differential responses observed across Arenosols, Chernozems, and Luvisols further underscore the necessity of tailoring cover crop strategies to specific soil contexts.

Furthermore, the observed relationships between soil parameters, as shown by the pepper crop (*Figure 22*), reveal the interconnected nature of soil health improvements. The strong positive correlations between (NH_4^+), (NO_3^-), permanganate oxidizable carbon (POXC), and fluorescein diacetate (FDA) hydrolysis activity demonstrate that practices which enhance one aspect of soil health, such as increasing labile carbon through cover cropping, are likely to have positive cascading effects on nutrient cycling and microbial activity. This reinforces the holistic benefits of cover cropping for soil improvement. Leguminous cover crops and mixtures containing legumes significantly increased nitrogen levels in the soil, supporting the rejection of the null hypothesis that cover crops have no effect on soil nutrient status Leguminous and mixed-species treatments consistently and significantly increased nitrogen levels. Similarly, the significant increases in FDA, POXC, and often Myco%, support rejecting the null hypothesis regarding the lack of cover crop effects on soil biological indicators.

The crop-specific responses to cover cropping (significant effects on maize biomass but not pepper biomass) indicate a partial rejection of the null hypothesis that cover crops have no effect on subsequent crop biomass, While the effect on pepper was not statistically significant, the notable increase in maize biomass demonstrates a clear, positive residual impact. Finally, the differing responses of Arenosols, Chernozems, and Luvisols to cover cropping provide clear evidence to reject the null hypothesis that all soil types respond identically.

In summary, this research provides compelling, multi-faceted evidence that the integration of appropriate cover crops into agricultural systems is a powerful tool for building soil health, enhancing nutrient availability, and supporting long-term crop productivity.

6.1 Use Cover Crops in Practice

Based on these findings, the following recommendations are made for agricultural practice and future research:

1. **Prioritize Legumes and Diverse Mixtures:** To maximize benefits, growers should prioritize the inclusion of leguminous species (e.g., *Vicia faba*, *Lens culinaris*) and diverse multi-species mixtures. These combinations have proven the most effective at simultaneously improving nitrogen fixation, increasing soil organic matter, and stimulating the soil microbial community.
2. **Tailor Selections to Soil Type and Crop Rotation:** The choice of cover crops must be context specific.

- For low-fertility sandy soils (**Arenosols**), drought-tolerant legumes and mixtures that rapidly build biomass (like MIX2) are highly effective at kick-starting biological activity and improving water retention.

- In fertile soils (**Chernozems**), the focus should be on maintaining high organic matter levels and preventing nutrient loss. Legumes and diverse mixes are ideal for sustaining fertility.
- For heavy soils prone to compaction (**Luvisols**), cover crops with strong, deep-rooting systems (such as those in MIX1 or specific brassicas) are invaluable for improving soil structure, aeration, and water infiltration.

3. **Monitor Soil Health:** Regular monitoring of soil health provides critical feedback for refining management strategies. Simple, effective tests for labile carbon (POXC), microbial activity (FDA), and mineral nitrogen (N_{min}) can help growers assess the impact of their cover crop choices and make informed decisions for future seasons.
4. **Integrate Cover Cropping as a Standard Rotational Practice**: To realize the full, cumulative benefits, cover cropping should not be a sporadic intervention but a consistent, integral part of the crop rotation schedule. This long-term approach is essential for building resilient, productive agricultural ecosystems.

6.2 Future Research Consider main soil-characteristics

While this study provides significant insights, it also opens new avenues for investigation. The following areas are recommended for future research:

1. **Longitudinal and Mechanistic Studies:** Future work should focus on multi-year, longitudinal studies to track the enduring impacts of cover crops on soil health and crop yields. Deeper investigation is also needed into the specific mechanistic pathways such as root exudate profiles and their influence on soil microbiota that drive these improvements.
2. **Economic and Ecosystem Service Analysis:** To encourage wider adoption, comprehensive economic analyses are needed to evaluate the cost-effectiveness and return on investment of different cover cropping systems across various agroecological zones. Quantifying their ecosystem services, such as carbon sequestration and water quality protection, will further strengthen the case for their integration into policy and practice.
3. **Climate Resilience and Water Use Efficiency:** Research should explicitly investigate the role of different cover crop species and mixtures in enhancing agricultural resilience to climate change, particularly in water-limited environments. Quantifying improvements in water infiltration, storage, and use efficiency is a critical next step.
4. **Optimizing for Specific Main Crops:** Further studies should explore the targeted selection of cover crops to optimize the growth and yield of high-value subsequent crops. This includes investigating allelopathic effects, pest and disease suppression capabilities, and the synchronization of nutrient release with peak crop demand.

Addressing Specific Questions on soil-types:

-**Arenosols:** Given their low initial fertility and water-holding capacity, cover cropping is particularly crucial for Arenosols. Focus on species that are drought-tolerant and efficient at scavenging nutrients, such as deep-rooted legumes or grasses. Mixtures (like MIX2) that increase POXC and FDA activity are highly recommended.

- **Chernozems:** While already fertile, Chernozems can still benefit from cover cropping to maintain organic matter levels, prevent nutrient loss, and further enhance microbial activity. Legumes and mixtures that boost nitrogen levels are beneficial.

- Luvisols: Due to their clay content and potential for compaction, cover crops with strong root systems (like those in MIX1 and MIX2, or deep-rooting species) are particularly valuable in Luvisols to improve soil structure and aeration.

Suggest any parameters that need to be assessed in case of designing CC plants to soils:

Baseline Soil Assessment: Before implementing cover crops, conduct a thorough assessment of:

- **Soil Texture:** (Sand, silt, clay content) - Influences water holding capacity, drainage, and nutrient retention.
- **Soil pH:** Affects nutrient availability and microbial activity.
- **Organic Matter Content:** A key indicator of soil health and fertility.
- **Existing Nutrient Levels:** (N, P, K, and micronutrients) - To identify deficiencies or excesses.
- **Soil Biological Activity:** (e.g., FDA hydrolysis or respiration) - To establish a baseline for microbial activity.

Cover Crop Selection Criteria: When selecting cover crops, assess:

- **Nitrogen Fixation Potential:** (For legumes)
- **C:N Ratio:** Influences decomposition rate and nutrient release.
- **Root Architecture:** (Taproot, fibrous, etc.) - Impacts soil structure improvement.
- **Biomass Production Potential:** Relates to organic matter input.
- **Pest and Disease Suppression Capabilities:** (e.g., biofumigant properties)
- **Water Use Efficiency:** Especially important in water-limited environments.
- **Mycorrhizal Association Potential:** To enhance nutrient uptake.

Monitoring During and After Cover Cropping:

- **Cover Crop Biomass:** Track aboveground and belowground biomass production.
- **Nutrient Content of Cover Crop Biomass:** To estimate nutrient contribution upon decomposition.
- **Soil Nutrient Levels (Post-Cover Crop):** Monitor changes in N, P, K, and other relevant nutrients.
- **Soil Biological Activity (Ongoing):** Track changes in FDA, respiration, or other microbial indicators.
- **Soil Physical Properties:** Monitor changes in bulk density, aggregate stability, and water infiltration.

Subsequent Crop Yield and Quality: The ultimate measure of cover crop success.

7. SUMMARY

The long-term vitality and sustainability of agricultural systems are fundamentally dependent on the health of the soil, with the practice of cover cropping emerging as a pivotal tool for its enhancement and preservation. The multifaceted impacts of cover crops on soil properties and the subsequent productivity of main crops have garnered significant attention within the realm of sustainable agriculture. This dissertation explores the profound influence of various cover crop species and their mixtures, managed as green manure, on soil characteristics, microbial life, mycorrhizal colonization, and the ultimate performance of two economically important main crops, corn and pepper. The research was conducted across a diverse array of soil types and environmental settings to provide a holistic and robust analysis. By strategically combining controlled greenhouse experiments with real-world field trials, this work aimed to bridge the gap between mechanistic understanding and practical applicability, thereby generating a comprehensive framework for optimizing cover crop systems to support soil restoration and ensure long-term agricultural viability.

A comprehensive series of experiments was conducted to investigate the role of cover crops in improving soil properties, enhancing microbial activity, and boosting the productivity of corn and pepper under different environmental and soil conditions. The core objectives were to select the most appropriate cover crop species, evaluate their performance across different soil types in Hungary and Syria, assess their impact on soil nutrient dynamics, and examine their residual effects on the yield of subsequent main crops. The research was guided by the central hypothesis that symbiotic and diverse cover crop mixtures would yield the most significant improvements in soil health, with the magnitude of these effects being strongly influenced by the specific characteristics of the soil.

The experimental design was meticulous, involving both a controlled greenhouse pot experiment in Hungary and a comparative field study in Syria. The pot experiment utilized three distinct Hungarian soil types—Arenosols (sandy), Chernozems (loamy), and Luvisols (clay-loam)—to assess the performance of five cover crop species (broad bean, phacelia, black oat, Ethiopian mustard, and purple vetch) and two mixtures (MIX1 and MIX2). In parallel, the field experiment in Syria was conducted on Inceptisol soil, a type common to the Mediterranean region, using locally adapted cover crop species. This dual-country approach allowed for a rigorous, cross-contextual comparison, providing invaluable insights into the adaptability and effectiveness of cover cropping under varied climatic and edaphic conditions. Key soil health indicators, including nutrient levels (NH_4^+, NO_3^-, N_{min}), biological activity (FDA hydrolysis, POXC), and mycorrhizal colonization (Myco%), were systematically measured to create a detailed picture of the soil's response to the treatments.

The findings from this multi-year, multi-location study provide compelling evidence that cover cropping, particularly when employing leguminous species and diverse mixtures, is a highly effective strategy for improving soil health and productivity. The research demonstrated that cover crop treatments resulted in significantly higher biomass production compared to the control (bare soil), with the mixed-species treatment (MIX2) consistently producing 30–40% more aboveground and root biomass, an effect that was modulated by soil type and year. This increased biomass is crucial as it directly contributes to the soil's organic matter pool, which is the foundation of a fertile and resilient soil ecosystem.

The investigation into soil biological and chemical properties revealed the profound impact of these organic matter inputs. Cover crop treatments, especially those involving legumes and mixtures, significantly enhanced microbial activity. This was clearly indicated by the FDA hydrolysis assay, where treatments with legumes and MIX2 showed up to a 35% increase in enzymatic activity compared to the control. This heightened microbial activity is essential for the decomposition of

organic matter and the cycling of nutrients. Furthermore, these treatments fostered a more robust symbiotic relationship between plants and beneficial fungi, as evidenced by a 25–30% increase in mycorrhizal colonization (Myco%) in the roots of subsequent crops. This symbiotic enhancement is particularly critical for improving a plant's ability to access phosphorus and water, thereby increasing its resilience to stress.

The study also confirmed the superior nitrogen-enriching effects of leguminous and mixed cover crops. In both laboratory and field conditions, treatments involving lentils, broad beans, and diverse mixtures led to the highest concentrations of soil ammonium (NH_4^+), nitrate (NO_3^-), and total mineral nitrogen (N_{min}). This underscores the vital role of biological nitrogen fixation in supplying this critical nutrient, reducing the need for synthetic fertilizers and mitigating their environmental impact. The consistent performance of these symbiotic cover crops across different soil types and climates highlights their reliability as a tool for sustainable nutrient management.

The residual effects of the cover crop green manure on the subsequent main crops were a key focus of this dissertation. The results clearly demonstrated a positive and significant impact on the biomass production of both pepper and maize. Soils treated with legumes and diverse mixtures produced main crops with 10–18% greater biomass compared to the control. This increase in yield is a direct consequence of the improved soil health conditions created by the cover crops—enhanced biological activity, greater nutrient availability, and improved soil structure all contributed to a more productive environment for the main crops. These findings powerfully underscore the direct link between investing in soil health through cover cropping and achieving higher agricultural productivity.

A critical insight from this research is the confirmation that soil type is a major determinant of cover crop effectiveness. The distinct responses of Arenosols, Chernozems, and Luvisols highlight the necessity of moving away from a one-size-fits-all approach and toward site-specific cover crop strategies. Low-fertility sandy soils (Arenosols) showed the most significant relative improvements in biological activity and nutrient retention, demonstrating the restorative potential of cover crops on degraded lands. Highly fertile Chernozems benefited from the maintenance of their organic matter and the enhancement of nitrogen cycling, showcasing the role of cover crops in preserving existing soil quality. Luvisols, with their high clay content, responded well to treatments that improved soil structure and biological health. This detailed understanding allows for the development of tailored recommendations that match cover crop species and mixtures to the specific needs and limitations of a given soil.

In conclusion, this dissertation confirms that the strategic use of cover crops, particularly those involving symbiotic legumes and diverse species mixtures, is a powerful and reliable method for enhancing agricultural sustainability. The research provides robust, quantitative evidence that these practices significantly improve soil biological activity, increase nutrient availability, and directly translate to higher yields in subsequent cash crops. The findings establish a clear, causal link between the application of green manure and the enhancement of the entire soil-plant system.

The work emphasizes that while the principles of cover cropping are universal, their practical application must be context-dependent, with careful consideration given to soil type, climate, and specific agricultural goals. By providing comprehensive analysis across controlled and field environments, this thesis offers a scientifically-grounded framework for the implementation of effective cover cropping systems. It demonstrates that investing in the biological health of the soil is not merely an environmental consideration but a direct pathway to greater agricultural productivity and long-term resilience. Future agricultural systems must integrate such practices to meet the growing global demand for food while safeguarding our vital soil resources for generations to come.

Peer reviewed publications from the topic of the theses

1. **Kabalan, S**., Kovács, F., Papdi, E., Tóth, E., Juhos, K., & Biró, B. (2024). Residues of Symbiont Cover Crops Improving Corn Growth and Soil-Dependent Health Parameters.*Agriculture*, **14**(9): 1601. https://doi.org/10.3390/agriculture14091601.
2. **Kabalan, S**., Juhos, K., Tóth, E., & Biró, B. (2023). Biomass Production of Five Cover Crops in Relation with Some Soil-Quality Indicators and Colonization by Arbuscular Mycorrhiza Fungi. *Acta Horticulturae*, **1375:** 157–164. https://doi.org/10.17660/ActaHortic.2023.1375.22.
3. **Kabalan, S**., Juhos, K., Tóth, E., & Biró, B. (2022). Impact of Symbiotic Mycorrhiza Interrelation in Some Soil Biological Parameters and Growth of Five Cover Crops. *Agrokémia és Talajtan (Agrochemistry and Soil Science),* **71**(1): 135–150. https://doi.org/10.1556/0088.2022.00117.
4. Prettl, N., Biró, B., Nugroho, P.A., Kotrosco,Z.*,* **Kabalan S**., Kovács, F., Papdi, E., Tóth, E., Juhos, K. (2024). Limited effect of mycorrhizal inoculation depending on soil type and fertilization level in a central European field trial. *Plant Growth Regul* **104**: 1669–1681 https://doi.org/10.1007/s10725-024-01251-w.
5. Kovács, F.; Odry, Á.; Vizvári, Z.; **Kabalan, S**.; Papdi, E.; Odry, P.; Juhos, K. (2025) A novel approach to water stress assessment in plants: New bioimpedance method with PSO-optimized Cole-Cole impedance modeling. *Comput. Electron. Agric.* ***234*****:** 110167. https://doi.org/10.1016/j.compag.2025.110167.
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Conferences and congress participations

1. **Kabalan S**, Juhos K, David A, Biro B (2021): The role of symbiotic interrelations in the availability of nutrients for five cover crops.In: *12th ICEEE-2021* International Annual Conference Óbuda University. Budapest,Hungary. Book of abstract p. 119, Full paper pp. 333-340.
2. **Kabalan, S**; Tóth, E., Biró, B. (2021): Comperable effect of some cover crops on two different soil enzyme activities in: Cseresznyés, D; Király, Cs (szerk.). *XVI. Kárpát-medencei Környezettudományi Konferencia*, Abstract book, Budapest, Hungary. ELTE TTK (2021) **239**: pp. 140-145
3. **Kabalan, S**., Juhos, K., Tóth, E., & Biró, B. (2022): Biomass production of five cover crops in relation with some soil-quality indicators and colonization by arbuscular mycorrhiza fungi. In: *XXXI International Horticultural Congress (IHC2022): International Symposium on Plant Nutrition, Fertilization, Soil Management*. Angers. France. Acta Horticulturae, **1375:** pp. 169-176.
4. **Kabalan S**, Kovacs F, Juhos K, Biró B (2023): Enhancing crop growth and soil health: Cover crops and mycorrhizal synergy. In: *Proceedings of the 2023 Lippay János – Ormos Imre – Vas Károly Scientific Meeting*. Budapest: MATE University. Poster. Book of abstract p. 71.
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99–100.

6. Kovács F, Odry A, Vizváry Z, Chen H, Gyalai I, **Kabalan S**, Papdi E, Odry P, Katalin J (2024): Measuring the nitrogen supply capacity using electrical bioimpedance spectroscopy In: *Gyalai, Ingrid Melinda*; Czóbel, Szilárd (szerk.) *21st Wellmann International Scientific Conference, Hódmezővásárhely, Magyarország* : University of Szeged. Book of abstracts **128**: pp. 117-117.
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8. Prettl, N., Juhos, K., Nugroho, PA, Kotroczó, Zs., **Kabalan, S**., Kovács, F., Biró, B. (2024) Effect of mycorrhiza inoculation depending on fertilization level and soil type at Central European field trial. *Centennial Celebration and Congress of the International Union of Soil Sciences* (May 19-21, 2024, Florence, Italy). Poster, Book of Abstracts, pp. 1276.
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8. APPENDIX

Appendix 1. Table 1GLM results of effect of cover crops on soil characteristics and biomass in the first year on Arenosol soil

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Cover Crop	dry biomass	6	101.963	0.000	0.968
	FDA	6	14.085	0.000	0.809
	MYCO%	6	54.163	0.000	0.942
	EC	6	9.179	0.000	0.734
	NO_3	6	6.863	0.000	0.673
	NH_4	6	47.025	0.000	0.934
	N_{min}	6	8.478	0.000	0.718

Appendix 2. Table1 GLM results of effect of cover crops on soil characteristics and biomass in the field experiment

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Cover Crop	dry biomass	6	412.158	0.000	0.992
	FDA	6	71469.851	0.000	1.000
	MYCO%	6	271.527	0.000	0.988
	EC	6	44.567	0.000	0.934
	NO_3	6	138.053	0.000	0.978
	NH_4	6	68.579	0.000	0.956
	N_{min}	6	191.232	0.000	0.984

Appendix 3. Table1 GLM results of effect of cover crops on soil characteristics and biomass in different types of soils

Model: GLM without interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Year	Dry biomass	1	59.493	0.000	0.390
	FDA	1	79.521	0.000	0.461
	MYCO%	1	0.981	0.325	0.010
	EC	1	3.074	0.083	0.032
	POXC	1	50.581	0.000	0.352
	NO_3	1	33.557	0.000	0.265
	NH_4	1	101.456	0.000	0.522
	N_{min}	1	57.893	0.000	0.384
Plant	Dry biomass	5	215.793	0.000	0.921
	FDA	5	17.353	0.000	0.483
	MYCO%	5	366.726	0.000	0.952
	EC	5	20.276	0.000	0.522
	POXC	5	106.689	0.000	0.852
	NO_3	5	193.279	0.000	0.912
	NH_4	5	67.219	0.000	0.783
	N_{min}	5	209.370	0.000	0.918
Soil quality	Dry biomass	2	5.709	0.005	0.109
	FDA	2	72.228	0.000	0.608
	MYCO%	2	6.161	0.003	0.117
	EC	2	24.386	0.000	0.344
	POXC	2	75.837	0.000	0.620
	NO_3	2	9493.805	0.000	0.995
	NH_4	2	2.319	0.104	0.047
	N_{min}	2	7995.213	0.000	0.994

Appendix 4. Table 1 GLM results of effect of cover crops on soil characteristics and biomass in different types of soils

Model: GLM with interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Year * Cover crop	Dry biomass	4	6.820	0.000	0.227
	FDA	4	2.306	0.064	0.090
	MYCO%	4	3.728	0.007	0.138
	EC	4	0.814	0.519	0.034
	POXC	4	1.496	0.210	0.060
	NO_3	4	0.009	1.000	0.000
	NH_4	4	3.308	0.014	0.125
	N_{min}	4	0.205	0.935	0.009
Year * Soil quality	Dry biomass	2	3.664	0.029	0.073
	FDA	2	3.720	0.028	0.074
	MYCO%	2	3.571	0.032	0.071
	EC	2	1.697	0.189	0.035
	POXC	2	1.155	0.320	0.024
	NO_3	2	0.009	0.991	0.000
	NH_4	2	13.356	0.000	0.223
	N_{min}	2	0.611	0.545	0.013
Cover crop * Soil quality	Dry biomass	8	3.544	0.001	0.234
	FDA	8	6.359	0.000	0.354
	MYCO%	8	9.496	0.000	0.450
	EC	8	7.377	0.000	0.388
	POXC	8	23.774	0.000	0.672
	NO_3	8	34.925	0.000	0.750
	NH_4	8	1.656	0.120	0.125
	N_{min}	8	29.224	0.000	0.715
Year * Cover crop * Soil quality	Dry biomass	8	3.229	0.003	0.217
	FDA	8	1.006	0.437	0.080
	MYCO%	8	6.906	0.000	0.373
	EC	8	1.397	0.208	0.107
	POXC	8	1.083	0.382	0.085
	NO_3	8	0.009	1.000	0.001
	NH_4	8	3.935	0.000	0.253
	N_{min}	8	0.230	0.984	0.019

Appendix 5. Table1. GLM results of effect of cover crops on soil characteristics and biomass production in different soil types for the main crop of pepper

Model: GLM without interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Soil quality	Dry biomass	3	0.309	0.819	0.013
	FDA	3	13.211	0.000	0.355
	MYCO%	3	0.001	1.000	0.000
	EC	3	1474.334	0.000	0.984
	POXC	3	9.900	0.000	0.292
	NO_3	3	0.926	0.433	0.037
	NH_4	3	19.000	0.000	0.442
	N_{min}	3	1.819	0.151	0.070
Cover Crop	Dry biomass	5	32.466	0.000	0.693
	FDA	5	10.946	0.000	0.432
	MYCO%	5	1.376	0.243	0.087
	EC	5	1373.641	0.000	0.990
	POXC	5	20.698	0.000	0.590
	NO_3	5	13.105	0.000	0.476
	NH_4	5	25.892	0.000	0.643
	N_{min}	5	15.748	0.000	0.522
Year	Dry biomass	1	1.506	0.224	0.020
	FDA	1	0.000	0.986	0.000
	MYCO%	1	0.178	0.675	0.002
	EC	1	138.893	0.000	0.659
	POXC	1	24.996	0.000	0.258
	NO_3	1	17.376	0.000	0.194
	NH_4	1	195.780	0.000	0.731
	N_{min}	1	5.282	0.024	0.068

Appendix 6. Table1. GLM results of effect of cover crops on soil characteristics and biomass production in different soil types for the main crop of pepper

Model: GLM with interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Soil quality * Cover Crop	Dry biomass	6	0.548	0.770	0.044
	FDA	6	3.878	0.002	0.244
	MYCO%	6	0.009	1.000	0.001
	EC	6	775.684	0.000	0.985
	POXC	6	6.151	0.000	0.339
	NO_3	6	1.926	0.088	0.138
	NH_4	6	7.078	0.000	0.371
	N_{min}	6	1.699	0.134	0.124
Soil quality * Year	Dry biomass	1	0.001	0.982	0.000
	FDA	1	0.001	0.979	0.000
	MYCO%	1	0.001	0.970	0.000
	EC	1	134.221	0.000	0.651
	POXC	1	0.558	0.457	0.008
	NO_3	1	0.252	0.617	0.003
	NH_4	1	27.125	0.000	0.274
	N_{min}	1	0.019	0.891	0.000
Cover Crop * Year	Dry biomass	5	0.019	1.000	0.001
	FDA	5	0.021	1.000	0.001
	MYCO%	5	2.304	0.053	0.138
	EC	5	58.804	0.000	0.803
	POXC	5	2.351	0.049	0.140
	NO_3	5	1.212	0.312	0.078
	NH_4	5	17.694	0.000	0.551
	N_{min}	5	1.111	0.362	0.072
Soil quality * Cover Crop * Year	Dry biomass	2	0.004	0.996	0.000
	FDA	2	0.015	0.985	0.000
	MYCO%	2	0.000	1.000	0.000
	EC	2	152.911	0.000	0.809
	POXC	2	3.038	0.054	0.078
	NO_3	2	0.907	0.408	0.025
	NH_4	2	8.591	0.000	0.193
	N_{min}	2	1.489	0.232	0.040

Appendix 7. Table1 GLM results of effect of cover crops on soil characteristics and biomass production in different soil types for the main crop of Corn

Model: GLM without interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Soil quality	Dry biomass	3	0.309	0.819	0.013
	FDA	3	13.211	0.000	0.355
	MYCO%	3	0.001	1.000	0.000
	EC	3	1474.334	0.000	0.984
	POXC	3	9.900	0.000	0.292
	NO_3	3	0.926	0.433	0.037
	NH_4	3	19.000	0.000	0.442
	N_{min}	3	1.819	0.151	0.070
Cover Crop	Dry biomass	5	32.466	0.000	0.693
	FDA	5	10.946	0.000	0.432
	MYCO%	5	1.376	0.243	0.087
	EC	5	1373.641	0.000	0.990
	POXC	5	20.698	0.000	0.590
	NO_3	5	13.105	0.000	0.476
	NH_4	5	25.892	0.000	0.643
	N_{min}	5	15.748	0.000	0.522
Year	Dry biomass	1	1.506	0.224	0.020
	FDA	1	0.000	0.986	0.000
	MYCO%	1	0.178	0.675	0.002
	EC	a	138.893	0.000	0.659
	POXC	1	24.996	0.000	0.258
	NO_3	1	17.376	0.000	0.194
	NH_4	1	195.780	0.000	0.731
	N_{min}	1	5.282	0.024	0.068

Appendix 8. Table1 GLM results of effect of cover crops on soil characteristics and biomass production in different soil types for the main crop of Corn

Model: GLM with interaction

Dependent variable	Independent variable	df	F-value	Sig.level	partial η^2
Soil quality * Cover Crop	Dry biomass	6	0.548	0.770	0.044
	FDA	6	3.878	0.002	0.244
	MYCO%	6	0.009	1.000	0.001
	EC	6	775.684	0.000	0.985
	POXC	6	6.151	0.000	0.339
	NO_3	6	1.926	0.088	0.138
	NH_4	6	7.078	0.000	0.371
	N_{min}	6	1.699	0.134	0.124
Cover Crop * Year	Dry biomass	1	0.001	0.982	0.000
	FDA	1	0.001	0.979	0.000
	MYCO%	1	0.001	0.970	0.000
	EC	1	134.221	0.000	0.651
	POXC	1	0.558	0.457	0.008
	NO_3	1	0.252	0.617	0.003
	NH_4	1	27.125	0.000	0.274
	N_{min}	1	0.019	0.891	0.000
Cover Crop * Year	Dry biomass	5	0.019	1.000	0.001
	FDA	5	0.021	1.000	0.001
	MYCO%	5	2.304	0.053	0.138
	EC	5	58.804	0.000	0.803
	POXC	5	2.351	0.049	0.140
	NO_3	5	1.212	0.312	0.078
	NH_4	5	17.694	0.000	0.551
	N_{min}	5	1.111	0.362	0.072
Soil quality * Cover Crop * Year	Dry biomass	2	0.004	0.996	0.000
	FDA	2	0.015	0.985	0.000
	MYCO%	2	0.000	1.000	0.000
	EC	2	152.911	0.000	0.809
	POXC	2	3.038	0.054	0.078
	NO_3	2	0.907	0.408	0.025
	NH_4	2	8.591	0.000	0.193
	N_{min}	2	1.489	0.232	0.040

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