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Soil Penetration, Moisture, and Infiltration Under Agroecological Management: Impacts of Conservation Tillage and Microbial Inoculants (*Rhizobium* spp., *Ensifer* spp., *Pseudomonas* spp., and *Bacillus* spp.) in Hungary

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Abstract

Modern agriculture faces increasing pressure to maintain productivity while reducing soil degradation, chemical inputs, and ecological footprint, making biologically based soil-improvement strategies highly relevant. This study examined whether microbial inoculation, combined with conservation tillage practices (loosening and no-tillage), can enhance soil physical quality during pea (*Pisum sativum*) cultivation in an agroecological market garden in Hungary. A 2 × 2 factorial field experiment was established, testing tillage (loosening vs. no-tillage) and microbial inoculation (with vs. without) in a randomized design with three replications per treatment (12 plots total). A single microbial application was performed prior to planting using a consortium of *Rhizobium* spp., *Ensifer* spp., *Pseudomonas* spp., and *Bacillus* spp. The research focused on (I) soil penetration resistance, (II) soil moisture dynamics, and (III) infiltration capacity, with most parameters measured before and after planting. Microbial inoculation significantly reduced penetration resistance under both tillage systems and influenced soil moisture behavior, indicating improved soil structure and water retention. Infiltration rate did not change significantly within the study period. Overall, the results demonstrate that microbial amendments can rapidly improve key soil physical properties, offering a practical, nature-based strategy for resilient, low-input farming systems.

Keywords: microbial inoculation; PGPB; conservation tillage; soil penetration resistance; soil moisture; soil infiltration; agroecological farming; soil physical properties

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1. Introduction

Climate change and global warming alter typical weather patterns, leading to extreme occurrences that jeopardize agricultural productivity and raise the vulnerability of food systems [1]. Agricultural practices, especially monocropping and extensive use of synthetic inputs, dramatically contribute to climate change [2]. Dependence on fossil-fuel-based external inputs in conventional farming increases farmers' debt and vulnerability to climate shocks [3]. Therefore, agroecology offers a transformative, equity-focused approach that applies ecological principles to build resilient food systems and address climate change and food insecurity [4–8]. This strategy promotes soil health, biodiversity, and reduces chemical inputs, all of which support sustainable agriculture and climate resilience [5,9,10].

Agroecological farming is based on a group of interconnected practices that improve ecosystem functioning, biodiversity, and soil health. Conservation tillage is one of the most widely adopted approaches, as it reduces soil erosion and improves water retention while enhancing soil structure, organic matter content, and promoting soil biodiversity and nutrient cycling [11,12]. No-tillage (NT) and reduced tillage (RT) are examples of conservation tillage techniques that substantially increase soil moisture content and infiltration rates. For instance, zero tillage with residue retention increased infiltration rates by about 15.2% over conventional tillage [13]. No-tillage with residue retention (NTR) improved soil biological indicators, as microbial biomass carbon increased by 25%, microbial nitrogen by 64%, and the microbial quotient by 57% compared with conventional tillage [14]. Conservation tillage practices increased Soil Organic Content (SOC) by 4.17% on average, with NT showing a larger increase of 5.92% compared to (Reduced Tillage) RT at 0.97% [15].

Crop rotation and intercropping further contribute to agroecological resilience by enhancing soil organic carbon (SOC) and nutrient availability [16–18], reducing soil erosion [19,20], improving aggregate stability [21,22], and increasing water infiltration and retention [16,21,23,24]. In addition, these practices help disrupt pest and disease cycles and promote biodiversity and ecosystem services [25,26].

For instance, a three-year rotation of wheat, maize, and soybean increased SOC concentrations from 16 to 19 gC kg soil^{-1} and SOC stock from 10.7 to 12 MgC ha^{-1} in the top 5 cm of soil [27]. Intercropping systems showed a 4% increase in SOC in the top 20 cm of soil compared to sole crops [28]. Intercropping *Alpinia oxyphylla* in rubber plantations increased soil water absorption by 52.93% in the surface soil layer [29].

Another promising agricultural practice for addressing the challenges associated with conventional fertilizers and soil degradation is the use of microbial inoculants. These beneficial microorganisms enhance nutrient-use efficiency by improving phosphorus solubilization, nitrogen fixation, and overall nutrient cycling, thereby promoting plant growth and yield while reducing fertilizer dependence [1,2,8,30,31]. In addition, they can increase plant tolerance to abiotic stress, suppress soil-borne pathogens [32–34], and improve soil health by enhancing microbial diversity and supporting organic matter dynamics [8,30,35,36].

Improving soil productivity is a central aim of agriculture. Traditionally, this has been achieved using chemical fertilizers to boost nutrient levels [37]. However, the rising costs of these inputs, along with their environmental drawbacks, have presented significant challenges. Excessive reliance on chemical fertilizers can degrade soil, reduce microbial diversity, cause nutrient imbalances, and contribute to water pollution through leaching and runoff. Moreover, their production is energy-intensive and contributes to greenhouse gas emissions and climate change [37–40]. In response, conservation agriculture promotes alternatives that reduce or eliminate the need for synthetic fertilizers. One such approach involves the use of beneficial soil microorganisms, such as *Pseudomonas* spp. and *Rhizobium* spp., which enhance nutrient availability, support root development, and contribute to overall soil health [41]. These microbial-based strategies not only offer a more cost-effective

solution for farmers but also align with the principles of sustainability and environmental stewardship [38,41].

Plant-growth-promoting microbes (PGPM) support plant development by facilitating key soil and plant processes, including organic matter decomposition and improved availability of essential nutrients such as nitrogen, phosphorus, potassium, iron, and magnesium [42]. Owing to these functions, microbial inoculants are increasingly recognized as integral components of integrated nutrient management systems, where they enhance nutrient-use efficiency, plant health, and crop productivity [43].

Soil inoculation involves the application of plant-growth-promoting bacteria (PGPB) to seeds, seedlings, leaves, or soil. After colonizing the rhizosphere or internal plant tissues, PGPB stimulate plant growth by improving nutrient uptake, regulating phytohormone levels, and inducing systemic resistance to biotic and abiotic stresses [44]. Numerous studies have demonstrated that PGPB not only increase crop yields but also improve food quality and safety by enhancing mineral availability and stimulating the production of bioactive compounds under diverse soil and climatic conditions [38,42,44,45].

Rhizobium inoculants play a key role in promoting nutrient uptake, particularly nitrogen, phosphorus, and potassium, thereby improving plant health and crop yields [46]. Their distinctive ability to form symbiotic root nodules with legumes enables biological nitrogen fixation, converting atmospheric nitrogen into plant-available forms [46]. This capacity, shared only with a limited group of specialized bacteria (e.g., *Azospirillum*, *Azotobacter*), makes rhizobia essential for sustainable agricultural systems.

In addition to *Rhizobium*, other beneficial bacteria such as *Bacillus*, *Pseudomonas*, and *Ensifer* can colonize legume nodules endophytically [47]. These non-rhizobial bacteria promote plant growth through hormone production, phosphate solubilization, and enzyme activities such as ACC deaminase, although they generally fix nitrogen less efficiently than rhizobia. Their coexistence with nitrogen-fixing bacteria can generate synergistic effects, enhancing soil fertility, crop productivity, and environmentally sustainable agricultural practices [48].

Among endophytic bacteria isolated from nodules, *Bacillus* and *Pseudomonas* are often dominant, reflecting their strong plant-growth-promoting capacity and stress tolerance [49]. Their frequent occurrence highlights the potential of beneficial microbial associations to improve crop performance, soil quality, and reduce reliance on chemical fertilizers.

To address these objectives, this study utilizes a microbial consortium composed of *Rhizobium*, *Ensifer*, *Pseudomonas*, and *Bacillus*. These genera were specifically selected for their complementary functional traits, including nitrogen fixation, phosphorus solubilization, and general plant growth promotion, ensuring that the consortium can enhance soil physical and biological properties under field conditions.

Immediate actions such as biofertilization are increasingly important for maintaining crop productivity and environmental sustainability, with legumes offering additional ecological benefits that enhance agroecosystem resilience [50]. Accordingly, this study focuses on evaluating the short-term, measurable effects of conservation tillage and microbial inoculation on key soil physical properties under pea cultivation in Hungarian soil conditions. By assessing changes in soil penetration resistance, moisture dynamics, and infiltration capacity, the research aims to provide practical evidence on how these agroecological practices can improve soil functioning and support more resilient, low-input farming systems.

Although conservation tillage and microbial inoculants are increasingly used to promote sustainable farming, we still have a limited understanding of how they work together to affect soil physical properties. Many studies have looked at crop performance or soil nutrients. These studies show that both practices lead to improvements in plant growth

and soil chemical conditions [51,52]. Research on microbial inoculants has also highlighted their role in supporting root development and biological activity in the soil [52,53]. However, while these findings suggest that agroecological practices can improve soil quality, there has been less focus on the physical aspects of soil health. Important factors like soil penetration, moisture retention, and water infiltration are crucial for stable and productive soil systems [54].

There are even fewer studies that combine conservation tillage and microbial inoculants. Conservation tillage is often studied on its own, primarily for its effects on soil porosity, compaction, and infiltration [55,56], while microbial inoculants are typically tested separately for their impact on soil aggregation and root–soil interactions. In some cases, soil compaction can even negate the positive effects of inoculants on soil hydraulic properties [53]. This highlights the importance of testing these practices together, as this study aims to determine whether conservation tillage can mitigate soil compaction and create a more favorable environment for inoculant efficacy. Since these practices are rarely evaluated in combination, clear evidence is still lacking on how they affect key physical properties such as penetration resistance, infiltration rate, and soil moisture under field conditions. Moreover, most existing studies are short-term or conducted in controlled settings, meaning their results may not fully represent real agricultural conditions. Therefore, additional field-based research is needed to understand how the interaction of conservation tillage and microbial inoculants influences soil physical structure in practice.

As mentioned previously, intensive tillage reduced organic inputs [57]. Continuous monoculture has accelerated soil organic matter depletion [58], with many agricultural soils losing between 20 and 60 percent of their original carbon stocks (SOC) since pre-industrial conditions [59]. In several intensively cultivated regions, soil organic matter levels have declined to below the critical threshold of approximately 2 percent, a benchmark considered essential for maintaining adequate microbial activity, effective nutrient cycling, and sufficient soil water-retention capacity [60]. The deterioration of soil structure due to intensive agriculture is further evidenced by diminished porosity, increased bulk density, and impaired root penetration, collectively constraining plant productivity and overall ecosystem functioning [61,62].

To overcome the limitations of previous work, the present research aims to evaluate how soil management interventions influence key soil physical properties in Hungarian agroecosystems. In particular, the study focuses on determining the extent to which conservation tillage practices, alone and in combination with microbial inoculants, can improve soil structure and functional performance. Accordingly, the following overarching research questions were established:

- How does conservation tillage affect soil penetration resistance, moisture dynamics, and infiltration capacity?
- What are the effects of microbial inoculants on soil penetration, moisture retention, and infiltration under different tillage systems (no tillage and loosening)?
- How do conservation tillage and microbial inoculants interact to influence overall soil structural integrity and functional efficiency?
- How do these combined practices contribute to long-term soil sustainability and support agroecological principles, such as enhancing soil health, reducing input dependency, and promoting resilient ecosystem functioning?
- How can the integration of conservation tillage and microbial-based soil amendments be translated into practical, economically viable, and regionally adaptable strategies for farmers, particularly within Hungarian agricultural conditions, to improve soil performance and crop productivity?

2. Materials and Methods

2.1. Materials

To measure soil penetration resistance, a penetrometer (Eijkelkamp, Giesbeek, The Netherlands) was utilized to evaluate compaction levels across different plots. Soil moisture content was determined using samples gathered with an auger (Eijkelkamp, Giesbeek, The Netherlands), which were then oven-dried in a drying cabinet (Memmert UFE, Schwabach, Germany) to calculate gravimetric moisture. The soil infiltration rate was measured with a single-ring infiltrometer (Eijkelkamp, Giesbeek, The Netherlands); a metal ring was driven into the soil, and a specified volume of water was added to determine the time taken for infiltration, thus characterizing soil permeability.

Given time constraints and capacity limitations, the research aims to offer a general overview of soil penetration, moisture, and infiltration during the experiment. Therefore, Sections 3 and 4 centers specifically on the data collected during the pea growth phase, which occurred in the second year of the study, the midway point of the experiment.

In the second year of the study (2024), peas (*Pisum sativum*) were cultivated. Organic pea seeds were sourced from Rédei Kertimag Zrt. (Réde, Hungary). The microbial inoculant applied consisted of selected beneficial soil bacteria, including *Rhizobium leguminosarum*, *Ensifer kummerowiae*, *Pseudomonas putida*, *Pseudomonas fluorescens*, *Bacillus megaterium*, and *Bacillus subtilis*. These commercial strains were supplied by *Phylazonit* company and were chosen for their potential to enhance soil nutrient cycling, root development, and plant growth.

2.2. Methodology

This research was initiated through an experimental trial conducted in a controlled garden environment designed to simulate real-world agricultural conditions while allowing for precise management of key variables. The study focused on three core agronomic practices: soil inoculation, crop rotation, and minimal soil tillage (loosening and no-till). Soil loosening was performed using a broadfork, initially to a depth of 20 cm and subsequently to 40 cm, while the no-till treatment involved no mechanical soil disturbance.

Each of these practices was incorporated with specific objectives: soil inoculation aimed to provide a cost-effective alternative to conventional chemical fertilizers by introducing beneficial soil microorganisms; crop rotation was implemented to enhance both ecological balance and economic efficiency, adhering to the principles of bio-intensive gardening; and deep tillage was replaced by alternative soil loosening and no-till to preserve soil structure and promote long-term soil health.

Preparation for potato cultivation started in 2023, and planting took place in April 2023. Soil inoculants were applied during planting to improve soil microbial activity. The potato crop was harvested in late July 2023, completing the initial phase of the experiment. The research then moved on to growing peas, with preparatory work and planting finished by late March 2024. Soil inoculation continued throughout the pea growing period to support soil microbial health. Peas were harvested in mid-June 2024.

Straw mulch during pea growing was applied to the soil surface. This practice was employed primarily to suppress weed growth, conserve soil moisture, and regulate soil temperature, thereby creating more favorable conditions for crop development and promoting overall soil health.

The collected data were visually represented using plot diagrams, providing an overview of variability and distribution. Statistical analysis was conducted using Analysis of Variance (ANOVA) in the R (Version 4.4.3) programming environment to determine the significance of differences observed between treatment groups and to draw conclusions regarding the effects of the implemented practices.

This methodology integrates agronomic techniques within a practical, market-oriented setting, aiming to balance ecological benefits with economic viability. The detailed procedures for experimental design, sample collection, laboratory analysis, and statistical evaluation are presented in the subsequent sections to ensure reproducibility and transparency.

2.2.1. Experimental Field Design and Setup at SZIA Agroecological Garden, MATE, Gödöllő

The practical phase of this research was conducted at the SZIA Agroecological Garden, located at the Hungarian University of Agriculture and Life Sciences (MATE) in Gödöllő, Hungary. The garden provided an ideal environment for controlled experimentation, enabling the investigation of sustainable soil management practices under realistic field conditions.

In April 2023, the garden was subdivided into twelve distinct plots, each measuring 80 cm in width and 300 cm in length. These dimensions were standardized across all plots to facilitate consistent and accurate data collection. The plots were carefully measured and spaced apart by additional beds, serving as physical barriers to prevent any potential cross-contamination between different microbial treatments. This spatial separation was critical for maintaining the integrity of the experimental design and minimizing treatment interference.

The experiment employed a randomized complete block design (RCBD) with a split-plot arrangement, replicated three times to ensure statistical robustness and account for environmental variability, such as soil fertility gradients and moisture differences. The design allowed precise assessment of the impacts of tillage and microbial inoculation on soil dynamics and crop growth.

Four treatment groups were established, each replicated three times, resulting in a total of twelve experimental plots:

- A− (Loosening without Microbes): Soil was subjected to loosening techniques without the addition of microbial inoculants.
- A+ (Loosening with Microbes): Loosening was combined with the introduction of beneficial microbial agents.
- B− (No-Tillage without Microbes): Soil remained undisturbed without microbial inoculation.
- B+ (No-Tillage with Microbes): No-tillage practices were applied alongside microbial inoculants to evaluate their combined effect on soil properties.

A visual representation of the experimental layout is provided in Figure 1 and offers an overview of the design and spatial organization of the study plots.

The experiment started with the careful application of the assigned tillage treatments for each plot. All procedures were performed with attention to detail to ensure reliable results. The main goal was to compare the effects of no-tillage and soil loosening, both with and without microbial inoculants, on soil properties and crop performance.

Figure 2 provides an in-depth description of the study area, highlighting the soil horizon profile and offering significant context regarding the soil-related elements of the experiment.

Figure 3 displays the garden's layout, created using QGIS (Version 3.34) and images from Google Earth (GPS coordinates: 47.5941° N, 19.3593° E).

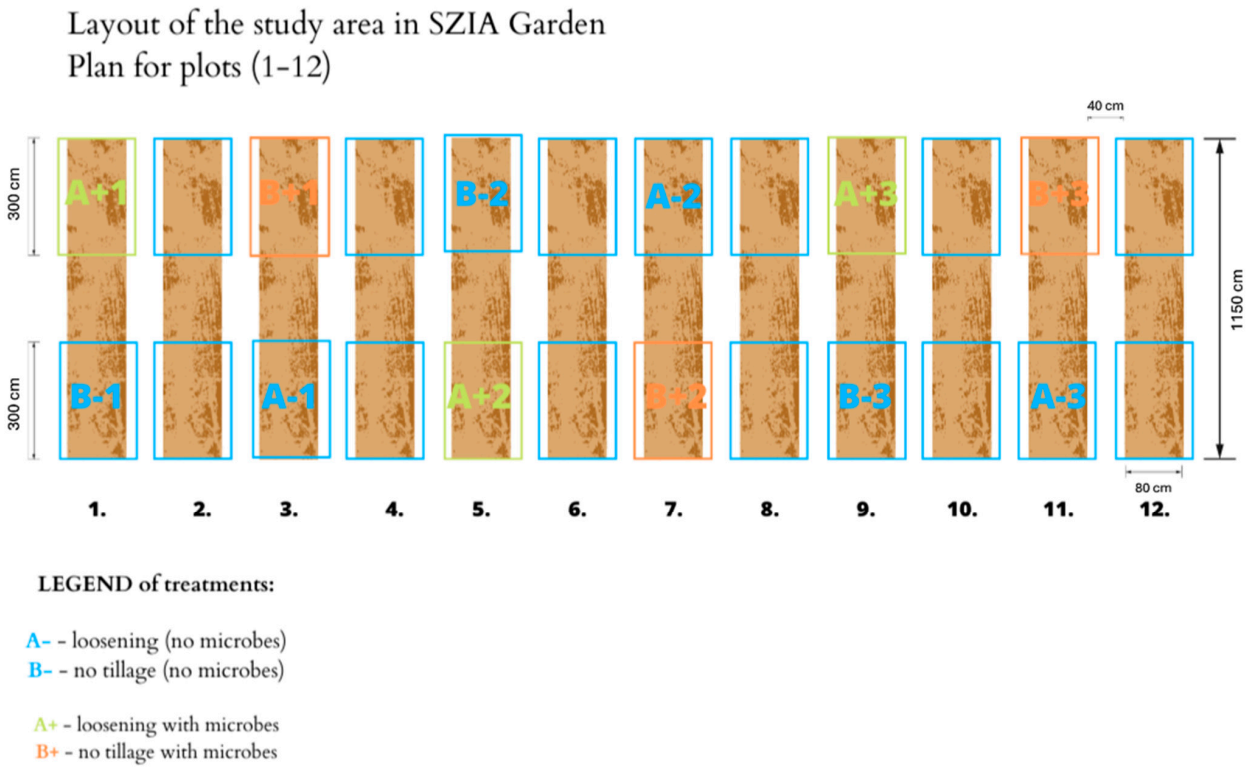


Figure 1. Experimental layout of the field plots used during the study (Source: Own work).

Location: SZIA Agroecological Garden
Landform: flat
Land use: horticulture
Temperature regime: Mesic
Moisture regime: Ustic
Parent material: sand

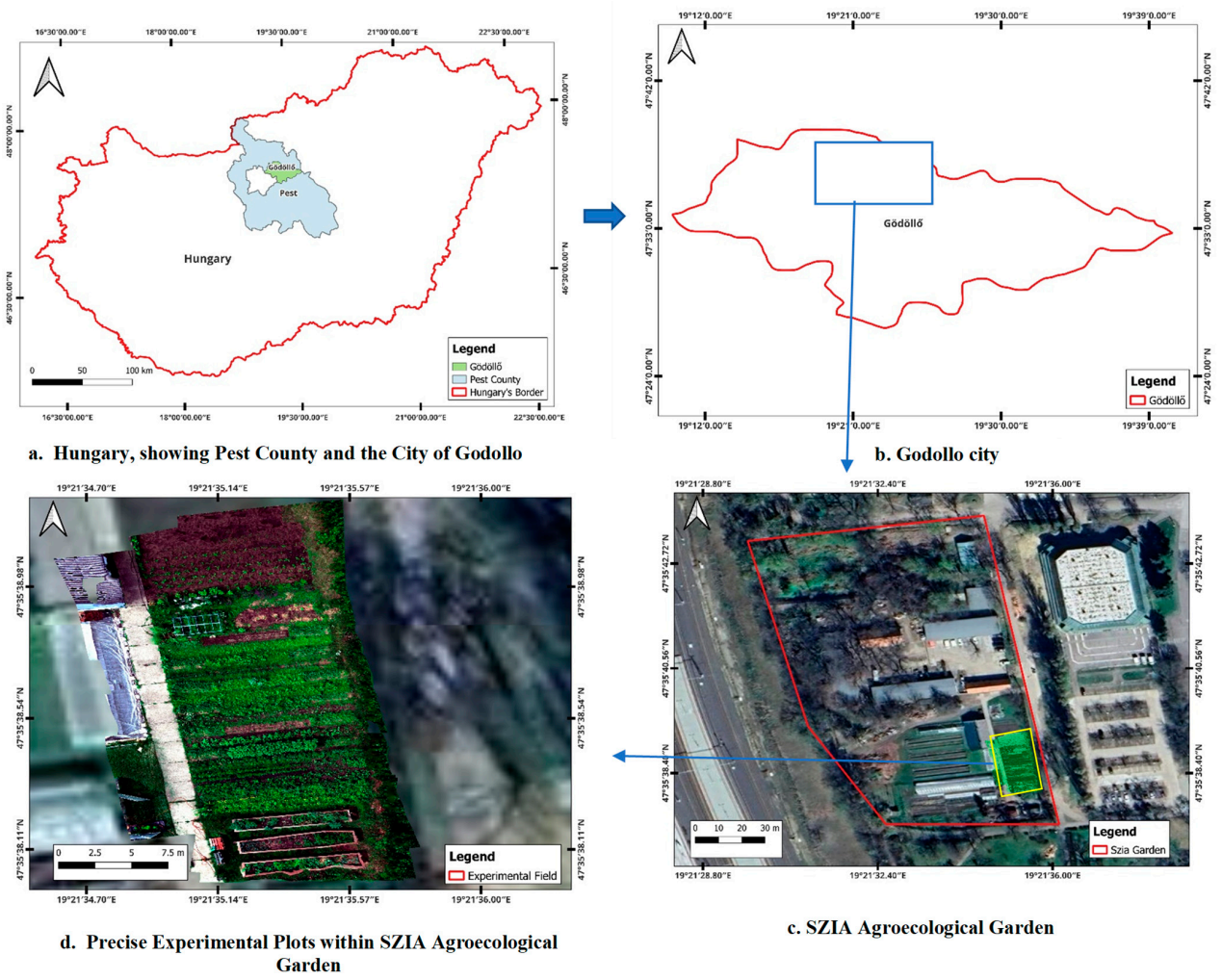


Apu (0-20cm)	Munsell dry (10 YR 3/2) and moist (10 YR 2/2) colour; sandy loam texture; weak, granular structure; sharp, wavy boundary; low $CaCO_3$ content (3.08%)
Au (20-40cm)	Munsell dry (10 YR 4/2) and moist (10 YR 3/1) colour; sandy loam texture; structureless; slight $CaCO_3$ content (1.3%)
Bbw (40-60cm)	Munsell dry (10 YR 4/4) and moist (10 YR 3/3) colour; sandy loam, structureless; single grain; no effervescence
2Bw1 (60-80cm)	Munsell dry (10 YR 4/4) and moist (10 YR 3/2) colour; loamy sand texture; structureless; single grain; no effervescence
2Bw2 (80-120cm)	Munsell dry (10 YR 4/3) and moist (10 YR 3/2) colour; loamy sand; structureless; single grain; no effervescence
2C (120-)	Munsell dry (10 YR 4/6) and moist (10 YR 3/4) colour; loamy sand texture; structureless; single grain; no effervescence

Analytical data

Genetic horizon	Depth (cm)	pH (H_2O)	pH (KCl)	SOM (%)	$CaCO_3$ (%)	Sand (%)	Silt (%)	Clay (%)	Texture
Apu	0-20	7.4	7.3	3,5	3.08	65.17	21.76	13.07	SL
Au	20-40	7.2	7.1	3,0	1.3	64.45	21.27	14.27	SL
Bbw	40-60	7.2	7.1	1,1	0	75.05	12.69	12.26	SL
2Bw1	60-80	7.3	7.0	0,9	0	81.47	8.68	9.86	LS
2Bw2	80-120	7.3	6.9	0,6	0	83.19	6.85	9.96	LS
2C	120-	7.3	6.8	0,3	0	82.82	6.01	11.17	LS

Figure 2. Description and profile of the soil horizons at the experimental site (Source: MATE Soil Research Team).



a. Hungary, showing Pest County and the City of Godollo

b. Godollo city

c. SZIA Agroecological Garden

d. Precise Experimental Plots within SZIA Agroecological Garden

Figure 3. Overview of the research site across four spatial scales: (**a**) Hungary with Pest County highlighted and the location of Godollo; (**b**) Administrative placement of Godollo within Pest County; (**c**) Detailed view of the specific experimental plot where the research was conducted; (**d**) Research area showing greenhouses and field structures with the experimental field. (Source: Own work).

2.2.2. Application of Soil Inoculants in Crop Cultivation

The use of microbial soil inoculants played an essential role in this study, which focused on improving nutrient availability and promoting crop growth in different plant varieties, including pea growth, like presented. The inoculants, provided by Hungarian *Phylazonit* company, featured carefully chosen strains of beneficial bacteria that are naturally found in the Carpathian Basin. This selection was made to ensure compatibility with the local ecosystem and to limit any disruption to the existing soil microbiota. Metagenome sequencing was also performed to confirm that the inoculated microorganisms were naturally present in the study soil and did not introduce any foreign species.

For the pea planting, the study employed application of microbial inoculants to assess their effect on legume growth and soil improvement. The bacterial composition for peas included *Rhizobium leguminosarum*, *Ensifer kummerowiae*, *Pseudomonas putida*, *Pseudomonas fluorescens*, *Bacillus megaterium*, and *Bacillus subtilis*. Symbiotic nitrogen-fixing strains (*Rhizobium leguminosarum* and *Ensifer kummerowiae*) constituted approximately 40% of the mixture, while the remaining 60% consisted of strains known for their soil regenerative capabilities, contributing to nutrient solubilization and pathogen suppression (see Table 1 for details).

In accordance with guidelines, the inoculant was mixed into the planting holes during seedbed preparation at the depth appropriate for pea sowing. The nitrogen-fixing bacteria facilitated biological nitrogen fixation, enriching soil nitrogen levels critical for legume development. Other bacteria enhanced nutrient bioavailability, supported root growth, and increased plant resilience against environmental stressors and diseases. The inoculant was applied at a concentration of 10^9 Colony-Forming Units (CFUs) per cm^3 to ensure targeted and effective inoculation.

Table 1. Composition of soil amendment mixture (Peas II year-2024) (Source: Phylazonit Catalogue).

Category	Strain	Function
Symbiotic Nitrogen Fixers (40%)	*Rhizobium leguminosarum*	Forms nitrogen-fixing nodules on legumes, enhancing soil fertility and reducing reliance on synthetic fertilizers
Symbiotic Nitrogen Fixers (40%)	*Ensifer kummerowiae*	Nitrogen-fixing bacterium that improves nitrogen availability through its symbiotic relationship with legumes
Soil-Regenerating Strains (60%)	*Pseudomonas putida*	Produces siderophores for enhanced iron availability and degrades organic compounds, promoting soil health
Soil-Regenerating Strains (60%)	*Pseudomonas fluorescens*	Biocontrol agent against pathogens and phosphate solubilizer, promoting plant health
Soil-Regenerating Strains (60%)	*Bacillus megaterium*	Phosphate solubilizer that enhances phosphorus availability and produces growth-promoting substances
Soil-Regenerating Strains (60%)	*Bacillus subtilis*	Suppresses pathogens and improves soil structure via exopolysaccharide production

2.2.3. Soil Physical Properties' Assessment: Penetration Resistance, Moisture Content, and Infiltration Rate

To evaluate the physical condition of the soil under different tillage systems and microbial inoculation treatments, a series of field and laboratory assessments were conducted.

This part of the study focused on three key soil physical parameters: soil penetration resistance, soil moisture content, and soil infiltration rate, which collectively provide insights into soil compaction, water availability, and hydrological performance. These parameters were measured across 12 experimental plots during the cultivation of peas (in the middle of the experiment) enabling comparative analysis across crop types and treatment combinations.

Soil Penetration Resistance

Soil penetration resistance was assessed as an indicator of soil compaction and its potential influence on root development, water movement, and microbial activity. Higher resistance values typically signify greater compaction, which may inhibit root penetration and reduce crop productivity.

- Instrumentation and Crop-Specific Methods: For pea cultivation, a penetrometer calibrated in kilopascals (kPa) was utilized. This device, provided by the university, allowed for precise pressure readings at depth (shown in Figure 4).
- Depth Intervals and Replication: Measurements were taken at four soil depth intervals: 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. Each depth was assessed three times per plot at randomly selected points to ensure statistical reliability.
- Timing of Measurements: For peas, measurements were taken at three growth stages: before planting, during early vegetative growth, and after harvest.

These measurements allowed for the analysis of soil compaction dynamics over time and under different treatment regimes.

Soil Moisture Content

Soil moisture content was evaluated to determine the availability of water in the root zone, which is essential for plant uptake, nutrient transport, and microbial activity.

- Sampling Procedure:

For soil moisture analysis, samples were collected from four depth intervals (0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm) in each plot. The soil from each depth was placed in individual zip-lock bags to preserve its moisture content during transport. Each plot yielded four separate samples, one per depth, which were immediately weighed in the field to record the fresh (wet) mass, then transported to the laboratory for further processing.



Figure 4. Soil Penetrometer (calibrated in kPa) (**1.**), Soil Auger for Moisture Sampling (**2.**), Infiltration Ring (**3.**), and Soil Penetrometer (color-coded scale) (**4.**) (Source: Own work).

- Timing: One sampling session was conducted during the active growth phase of each crop: once during pea cultivation.
- Laboratory Analysis:

In the lab, each sample was again weighed for its fresh (wet) mass, then placed in a drying oven at 105 °C for 24 to 48 h, or until a constant dry weight was achieved. After drying, the samples were reweighed, and gravimetric soil moisture content was calculated using the formula:

$$\text{Soil Moisture } (\%) = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100$$

Soil Infiltration Rate

Soil infiltration rate is a key indicator of soil structure and porosity, affecting water availability, erosion risk, and nutrient leaching. Field infiltration tests were conducted using the ring infiltrometer method.

- Equipment and Procedure:

A metal ring infiltrometer (shown in Figure 4) was inserted vertically into the soil to a uniform depth across all plots. A measured volume of water was poured into the ring using a calibrated measuring cup.

- Observation Intervals:

The infiltration of water into the soil was timed and recorded at 1, 2, 3, 4, 5, 10, 15, 20, 25, and 30 min intervals. The volume of water absorbed at each interval was recorded to construct infiltration curves, representing the dynamics of water movement in the soil profile.

- Repetitions:

Each measurement was conducted once per plot, before and after planting, and data were used to evaluate differences in infiltration behavior between treatment groups.

2.3. Data Statistics and Analysis

All statistical analyses were performed using R (version 4.4.3). Soil penetration resistance, soil moisture, and soil infiltration rate were analysed at different time points (Before, During, and After crop establishment). Mean values and standard errors were calculated for each treatment and soil depth combination. Soil penetration resistance data were log-transformed [log (x + 1)] to meet model assumptions. Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Analysis of variance (ANOVA) was conducted separately for each time point using the aov() function. A two-way ANOVA was applied to soil penetration resistance to evaluate the effects of Treatment, Soil Depth, and their interaction, whereas one-way ANOVA was used for soil moisture and soil infiltration rate. When significant effects were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was used for multiple comparisons employing the agricolae package. Graphical outputs were generated using ggplot2, including line plots for soil penetration resistance across depths and bar plots with error bars for soil moisture and infiltration rate. Statistical significance was set at $\alpha = 0.05$, and 95% confidence intervals were reported where appropriate.

3. Results

Each figure below presents the R-generated results for Soil Penetration, Soil Moisture and Soil Infiltration tests. Bar graphs (left panels) show the mean rates for each treatment, while the accompanying Tukey pairwise comparison plots (right panels) display the differences in means with 95% confidence intervals, indicating whether any statistically significant differences exist among the treatment groups.

In March 2024, before planting of peas, Penetration Resistance, Soil Moisture and Soil Infiltration were measured. In June 2024, during growth of peas, Penetration Resistance was measured. In July 2024, after harvesting, again Penetration Resistance, Soil Moisture and Soil Infiltration were measured.

Figure 5 presents results for Soil Penetration Resistance measured before, during, and after planting of peas. The figure includes a comparison of mean values across these time points, highlighting changes and trends over the course of the planting process with peas.

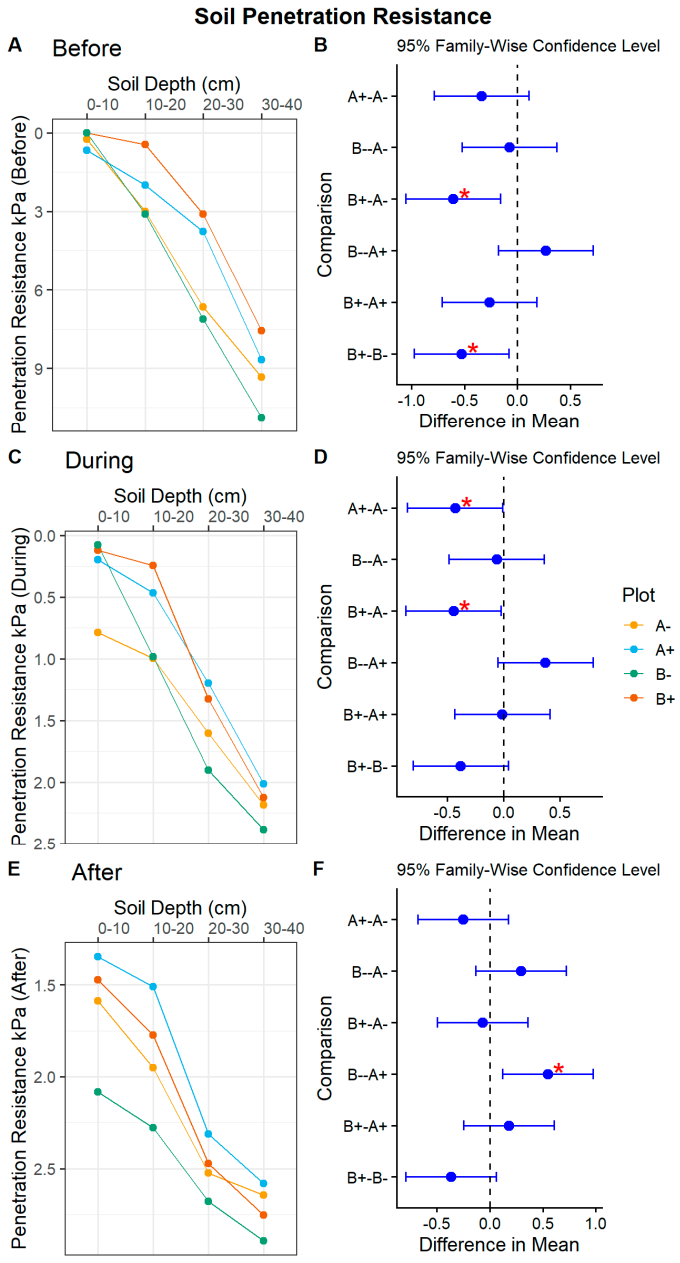


Figure 5. Soil Penetration Resistance Before, During, and After Planting (Peas II year-2024) (Source: Own work). (**A**) Before planting (Line Plot)—Shows penetration resistance increasing with soil depth across plots A−, A+, B−, and B+. (**B**) Before planting (Tukey HSD)—Displays mean differences between plot pairs; significant differences are marked for B+/A− and B+/B−. (**C**) During planting (Line Plot)—Shows penetration resistance across the four depths during the planting phase. (**D**) During planting (Tukey HSD)—Displays mean differences between plot pairs; significant differences are marked for A+/A− and B+/A−. (**E**) After planting (Line Plot)—Shows penetration resistance across the four depths following the planting phase. (**F**) After planting (Tukey HSD)—Displays mean differences between plot pairs; a significant difference is marked for B−/A+.

Since significant differences were observed, as indicated by the red asterisks (*) in the comparison plots, a detailed statistical analysis using Tukey's Honest Significant Difference (HSD) test was conducted to further explore pairwise differences between treatments. This analysis was carried out separately for the periods before, during, and after planting of peas to capture any changes over time. The results of these comparisons, including confidence intervals and significance levels, are presented in Tables A1–A3, respectively, available in Appendix A. These tables provide a clearer understanding of where significant differences occurred among the treatments at each stage.

Soil moisture was measured once during the planting of peas, using both fresh and oven-dried soil samples. The results, presented in Figure 6, reflect the moisture content by comparing the weight of the soil before and after drying. This provides an indication of the actual soil moisture level at the time of sampling.

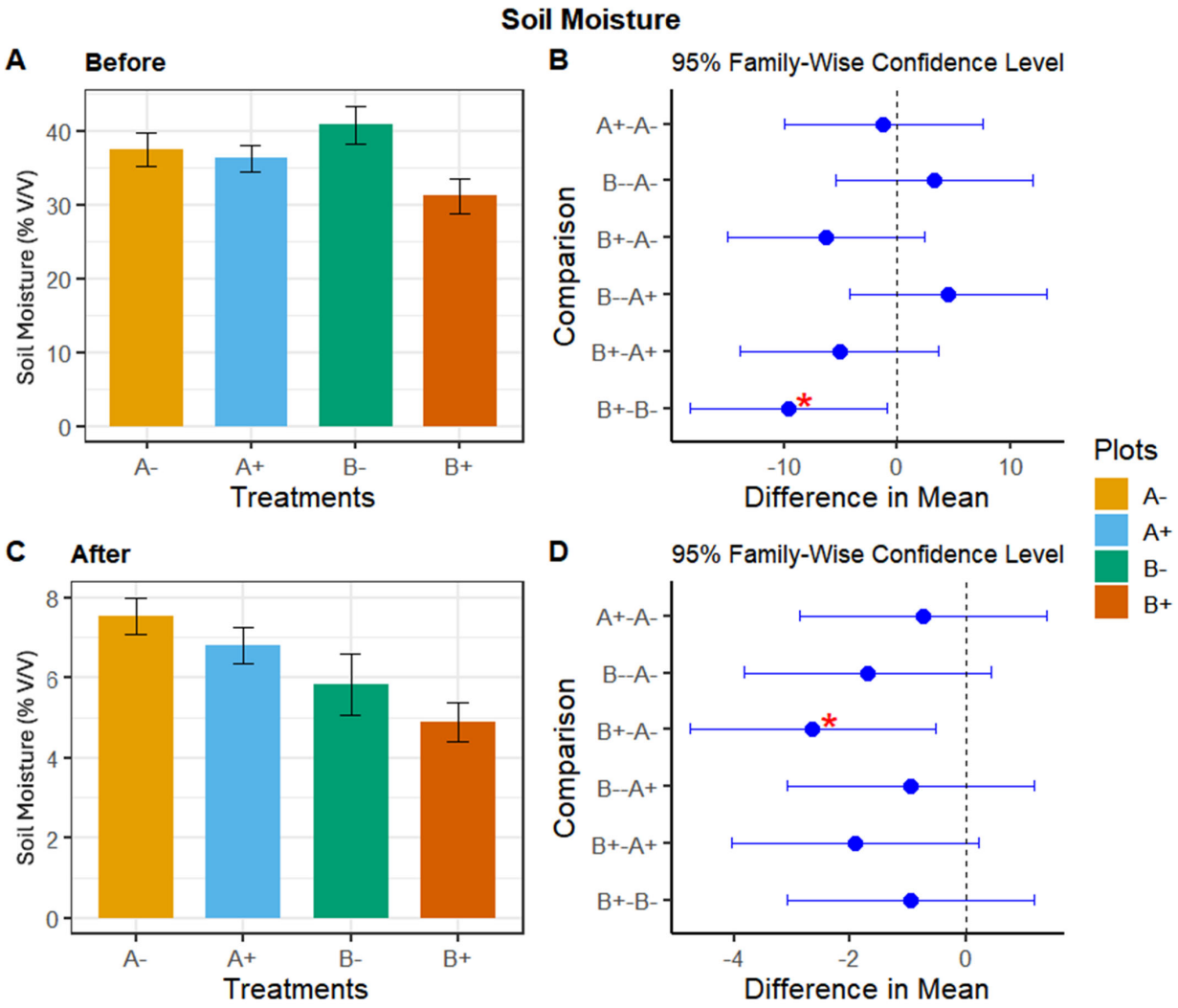


Figure 6. Soil Moisture Content During Pea Planting (II year-2024) Based on Fresh and Dry Soil Weights (Source: Own work). (**A**) Before planting (Bar Plot)—Shows soil moisture levels across treatments A−, A+, B−, and B+ before planting. (**B**) Before planting (Tukey HSD)—Displays mean differences between plot pairs; a significant difference is marked for B+/B−. (**C**) After planting (Bar Plot)—Shows soil moisture levels across the four treatments following the planting phase. (**D**) After planting (Tukey HSD)—Displays mean differences between plot pairs; a significant difference is marked for B+/A−.

Significant variations in soil moisture, as indicated by the red asterisks (*) in the comparison plots, prompted a detailed statistical assessment using Tukey's Honest Significant

Difference (HSD) test to examine pairwise differences among treatments. This analysis was performed separately for each planting, considering both fresh and dry samples (before and after) to capture temporal changes. The outcomes of these comparisons, including confidence intervals and significance levels, are summarized in Tables A4 and A5, respectively, available in Appendix A. These tables offer a clearer depiction of where significant differences occurred among treatments at each stage.

Figure 7 presents the soil infiltration rate measured before and after planting peas across different treatments.

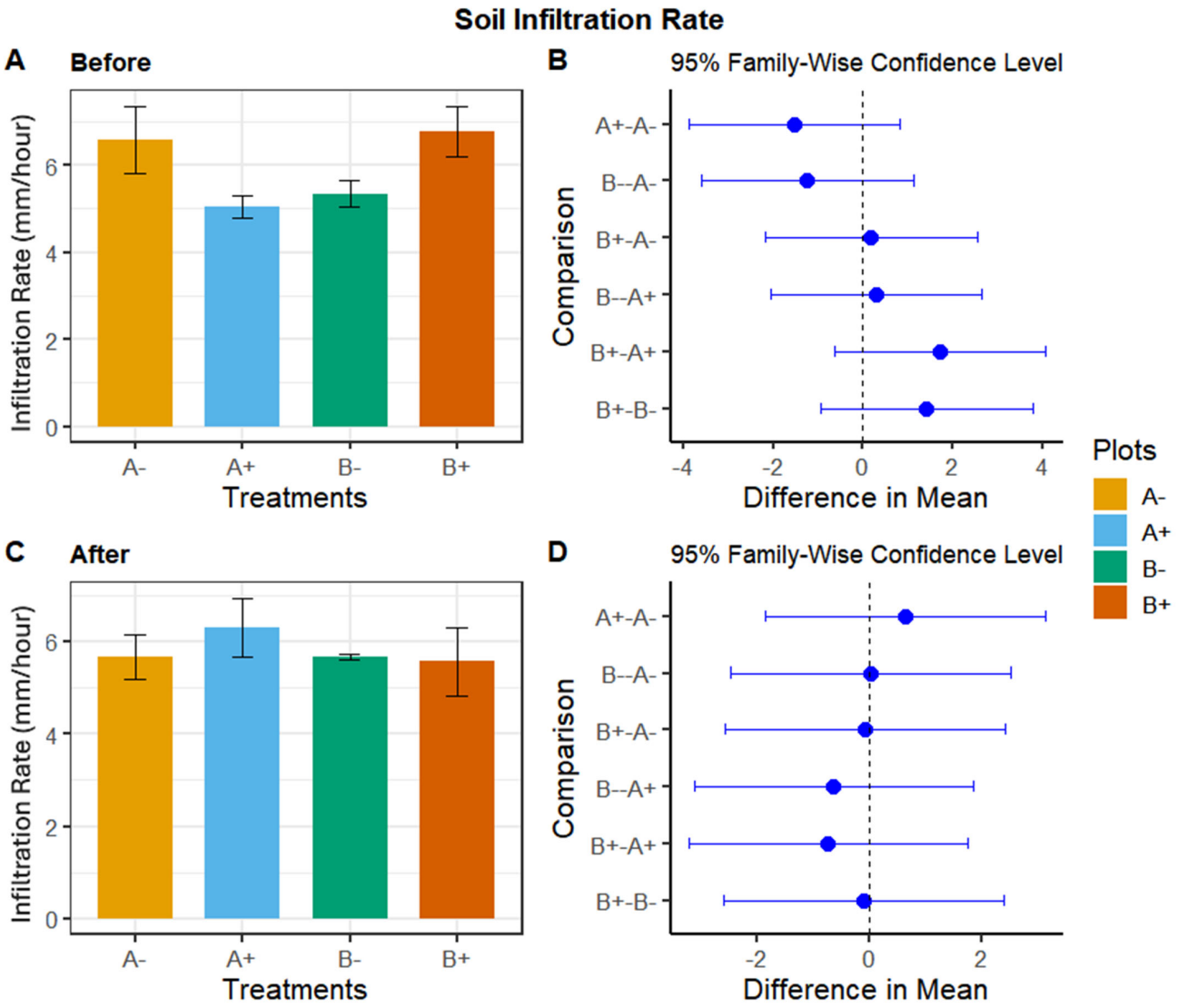


Figure 7. Soil Infiltration Rate Before and After Pea Planting (II year-2024) Across Treatments (Source: Own work). (**A**) Before planting (Bar Plot)—Shows soil infiltration rates across treatments A−, A+, B−, and B+ before planting. (**B**) Before planting (Tukey HSD)—Displays mean differences between plot pairs; no significant differences are observed as all confidence intervals cross the zero line. (**C**) After planting (Bar Plot)—Shows soil infiltration rates across the four treatments following the planting phase. (**D**) After planting (Tukey HSD)—Displays mean differences between plot pairs; no significant differences are observed following the planting phase.

4. Discussion

Concerning soil penetration, the application of loosening or no-tillage, paired with or without microbes, revealed considerable variation in soil penetration resistance, as indicated by Tukey HSD pairwise comparisons before, during, and after planting. Notably,

the introduction of microbial inoculants, whether combined with loosening or no-tillage, frequently resulted in statistically significant differences in penetration resistance compared to their non-microbial counterparts. Loosening without microbes (A−) generally showed higher soil penetration resistance compared to loosening with microbes (A+), though this difference was not always statistically significant. The addition of microbes (A+) appeared to enhance soil structure, likely through increased biological activity that promotes aggregation and reduces compaction. No-tillage treatments (B− and B+) serve as important comparisons. B−, no-tillage without microbes, often exhibited higher resistance, but integrating microbial inoculants (B+) with no-tillage significantly reduced resistance, indicating improved soil porosity and structure, perhaps due to microbe-driven processes like organic matter decomposition and stabilization. The most prominent differences, marked as significant in Tukey's tests, arose between B+ (no-tillage with microbes) and A+ (loosening with microbes), as well as between B+ and B−, highlighting the substantial effect of combining no-tillage practices with microbial amendments. These findings suggest that microbial treatments can offset negative impacts of soil compaction or lack of disturbance in no-tillage systems, leading to more favorable soil physical properties even under reduced mechanical intervention. The patterns of significance and resistance change before, during, and after planting indicate both immediate and sustained effects of management and microbial inputs. Significant improvements due to microbial inoculation persisted after planting, underlining the long-term benefits for soil health, especially in conservation tillage systems. This comparative analysis underscores the potential for integrating microbial amendments into both loosening and no-tillage management to maximize soil physical health. For practitioners, it means that microbial inoculants can be a key factor in enhancing root growth environments, reducing compaction, and supporting resilient agroecosystems, particularly where tillage reduction is part of sustainable farming goals. These results are strongly supported by findings in the soil science literature. Studies have shown that tillage interventions generally reduce soil penetration resistance, especially in the upper soil layers, enabling easier root penetration and improving soil aeration compared to no-tillage systems, which can lead to compaction if not managed properly. For example, several studies documented that zero-tilled soils have higher penetration resistance than ploughed or harrowed soils, and that the effect of tillage on lowering resistance is often temporary, with compaction returning over time [63,64]. Furthermore, recent research emphasizes the value of microbial inoculants in improving soil structure and mitigating compaction, particularly in conservation systems. Microbial practices, when combined with no-tillage or reduced tillage, have been shown to significantly lower penetration resistance and enhance soil physical properties, supporting both crop performance and long-term soil health. These alignments affirm that the observed treatment effects on soil penetration resistance in this study are consistent with established scientific trends.

Regarding soil moisture, the results show statistically significant differences in soil moisture among treatments, both before and after drying, with the most notable contrasts between the B+ and B− treatments. The pairwise Tukey HSD test indicates that, before drying, the B+ treatment had significantly lower soil moisture compared to the B− treatment (difference: −9.9966, $p = 0.0272$), and after drying, B+ was again significantly lower than A− (difference: −2.6399, $p = 0.0102$), as visualized by the non-overlapping confidence intervals in the summary plots. These findings suggest that both the fresh and dried soil moisture content were strongly affected by the applied treatments, with B+ consistently showing lower moisture retention as compared to other treatments. This is in line with other studies using the Tukey HSD test, where significant differences in soil moisture have been detected between certain irrigation or management treatments, indicating that soil amendments, management, or even specific plant–microbe interventions can create

measurable differences in soil water retention capacity. Studies have repeatedly shown that soil moisture responds sharply to both biological treatments and physical processes like drying and rewetting. Similar to the present results, significant moisture differences were found using Tukey HSD tests among irrigation treatments, leading to variable carbon and nutrient cycling responses [65]. This aligns with the pronounced differences between B+ and B− in the dataset. Further, it is documented that soil moisture modulates the activity and competitive effects of soil microbes, which in turn alters plant community feedback and soil nutrient dynamics, potentially explaining why some treatments retain less water than others [66,67]. The drying–rewetting process itself is known to cause biogeochemical changes in soils, disrupting microbial biomass and altering nutrient availability and carbon release. This is relevant for interpreting why the relative ranking of the treatments did not shift drastically after drying, as physical changes in water content may reinforce existing differences established by biotic or treatment effects. The consistently lower moisture under B+ treatment could indicate heightened microbial decomposition, altered soil structure, or enhanced nutrient cycling tied to the specific treatment. In literature, high soil microbial activity and certain plant–microbe manipulations have been shown to accelerate water loss or soil organic matter turnover, sometimes leading to lower soil moisture content. The visual confidence plots confirm these statistical results, highlighting that only pairwise treatment comparisons involving B+ versus B− or A− reach the threshold of significance. This underscores the reflection of the detected differences and matches documented expectations from similar agricultural and ecological studies. These findings contribute to the broader understanding that soil management strategies can dramatically affect soil moisture dynamics even after a drying cycle. This is especially relevant in agroecological contexts, where soil moisture regulation is key to improving plant growth, crop yield, and resilience to drought. The literature supports that such changes in moisture also translate into plant performance, nutrient cycling, and longer-term soil health, suggesting that selecting soil management/regeneration strategies should account for their impact on soil water dynamics. In summary, the results align with broader literature trends showing that targeted treatments can cause pronounced, statistically significant variations in soil moisture. These differences are persistent through drying cycles and have important implications for soil–microbe–plant interactions and agroecosystem management.

Soil infiltration rate was measured both before and after planting in the different treatments, yet no significant differences emerged among the groups at either time point. This pattern highlights that, under the given conditions, neither tillage practice nor microbial inoculation, nor the transition from pre-planting to post-establishment led to measurable changes in infiltration. In both pre-planting and post-planting measurements, mean infiltration rates were similar across the four treatments, with overlapping error bars and family-wise confidence intervals. This suggests a degree of stability in soil structure or water movement properties regardless of treatment or crop establishment. Literature shows that the effect of planting (crop establishment) on infiltration is often variable. Some studies indicate that as plant roots develop, they can increase infiltration by improving soil structure and pore connectivity. However, in managed agricultural systems, these changes may require longer periods or more intense biological activity to be measurable. Studies have shown that infiltration can either improve or remain unchanged after planting, depending on factors like soil type, cropping system, and management duration [68,69]. For example, in one of the studies, a linear increase in infiltration rate with plant age and root development has been found, but this effect was strong on soils with more responsive structures and under long-term vegetation [68]. Infiltration rates sometimes remain stable after planting when initial soil conditions (such as compaction or aggregate stability) dominate water movement, and when root growth or microbial activity are not sufficient

to alter these properties within the timescale of the study [70]. The lack of observable change before and after planting in this study suggests that under the tested management conditions, or over the experimental duration, root or microbial effects on infiltration were modest. Root growth, while known to increase soil porosity in some contexts, may not have reached a threshold to produce measurable differences. Literature reviews conclude that the greatest and most consistent improvements in infiltration follow sustained use of cover crops, organic amendments, or multi-season conservation practices, rather than single interventions or short trials [71]. The results here are consistent with such findings, supporting the idea that single-season or modest biological interventions may not always yield significant immediate impacts on soil infiltration dynamics [72]. In summary, infiltration rate did not differ significantly between treatments or from before to after planting, which is well-aligned with existing literature showing that observable changes in infiltration may require longer-term interventions or more transformative management practices.

5. Conclusions

The study provides several important scientific contributions regarding the use of microbial inoculants and conservation tillage to improve soil physical properties. Microbial inoculation enhanced soil structure by reducing penetration resistance across both tillage systems, with the most pronounced effect observed in no-tillage plots with microbes (B+), which exhibited significantly lower resistance than no-tillage without microbes (B−) and loosening with microbes (A+). Loosening without microbes (A−) showed the least improvement, indicating that reduced soil disturbance amplifies the benefits of microbial amendments. Soil moisture dynamics were also significantly affected by treatment, with B+ plots demonstrating lower moisture content before drying compared to B− and lower moisture after drying than A−, suggesting that microbial inputs actively influence water retention and interact with tillage management to modify soil hydrological behavior. In contrast, infiltration rates did not differ significantly among treatments, indicating that short-term or single-season interventions may be insufficient to alter water entry dynamics and that sustained application or long-term structural changes may be required.

The novelty of this research lies in its integrated evaluation of key soil physical properties under a combined management approach rarely assessed in a single field experiment:

- Assessment of soil penetration, moisture dynamics, and infiltration under different tillage intensities (loosening vs. no-tillage) with and without microbial inoculation.
- Demonstration that microbial inoculation improved soil penetration resistance and moisture retention, particularly under no-tillage, while short-term effects on infiltration were minimal, highlighting the need for longer-term soil management to enhance water movement.
- High replicability, as the approach can be scaled to larger fields by adjusting microbial doses.
- These results provide novel insights into the early regenerative effects of microbial inoculants on soil physical properties in small-scale agroecological vegetable systems.

While these findings highlight the potential of combining microbial inoculants with conservation tillage to improve soil compaction and moisture behavior, the study has some limitations. First, the experiment was conducted over a single growing season, which may limit the generalizability of results to longer-term field conditions. Second, only selected soil physical properties were measured, without detailed quantification of microbial biomass, soil aggregation, or root dynamics, which could further clarify the underlying mechanisms. Despite these constraints, the study provides a practical, nature-based strategy for enhancing soil functioning and supporting resilient, low-input agroecological systems.

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Abbreviations

The following abbreviations are used in this manuscript:

MATE	Magyar Agrár- és Élettudományi Egyetem (Hungarian University of Agriculture and Life Sciences)
NT	No tillage
NTR	No-tillage with residue retention
RT	Reduced tillage
SOC	Soil organic content
Spp.	Species pluralis

Appendix A

Table A1. Tukey HSD Pairwise Comparisons of Soil Penetration Resistance Before Planting (Peas II year-2024).

Comparison	Difference in Means	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Adjusted *p*-Value	Significance
A+-A−	−0.34116	−0.78766	0.10534	0.19753	Not significant
B−-A−	−0.07768	−0.52418	0.36882	0.96896	Not significant
B+-A−	−0.60533	−1.05183	−0.15883	0.00322	**Significant**
B−-A+	0.26348	−0.18302	0.70998	0.41910	Not significant
B+-A+	−0.26417	−0.71067	0.18233	0.41674	Not significant
B+-B−	−0.52765	−0.97414	−0.08115	0.01351	**Significant**

Table A2. Tukey HSD Pairwise Comparisons of Soil Penetration Resistance During Planting (Peas II year-2024).

Comparison	Difference in Means	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Adjusted *p*-Value	Significance
A+-A−	−0.4304	−0.8524	−0.0083	0.0438	**Significant**
B−-A−	−0.0625	−0.4846	0.3596	0.9804	Not significant
B+-A−	−0.4446	−0.8667	−0.0226	0.0347	**Significant**
B−-A+	0.3679	−0.0542	0.7896	0.1108	Not significant
B+-A+	−0.0143	−0.4363	0.4077	0.9998	Not significant
B+-B−	−0.3821	−0.8041	0.0399	0.0909	Not significant

Table A3. Tukey HSD Pairwise Comparisons of Soil Penetration Resistance After Planting (Peas II year-2024).

Comparison	Difference in Means	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Adjusted *p*-Value	Significance
A+-A−	−0.2502	−0.6757	0.1754	0.4226	Not significant
B−-A−	0.2954	−0.1302	0.7210	0.2749	Not significant
B+-A−	−0.0690	−0.4945	0.3566	0.9747	Not significant
B−-A+	0.5456	0.1200	0.9712	0.0060	**Significant**
B+-A+	0.1812	−0.2444	0.6068	0.6850	Not significant
B+-B−	−0.3644	−0.7899	0.0612	0.1210	Not significant

Table A4. Tukey HSD Pairwise Comparisons of Soil Moisture for Fresh Samples (Before Drying) (Peas II year-2024).

Comparison	Difference in Means	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Adjusted *p*-Value	Significance
A+-A−	−1.2004	−9.9524	7.5516	0.9822	Not significant
B−-A−	3.3131	−5.4389	12.0651	0.7358	Not significant
B+-A−	−6.2835	−15.0355	2.4685	0.2299	Not significant
B−-A+	4.5135	−4.2385	13.2656	0.5102	Not significant
B+-A+	−5.0831	−13.8351	3.6689	0.4075	Not significant
B+-B−	−9.5966	−18.3486	−0.8446	0.0272	**Significant**

Table A5. Tukey HSD Pairwise Comparisons of Soil Moisture for Dry Samples (After Drying) (Peas II year-2024).

Comparison	Difference in Means	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Adjusted *p*-Value	Significance
A+-A−	−0.7327	−2.8560	1.3907	0.7864	Not significant
B−-A−	−1.6933	−3.8166	0.4301	0.1562	Not significant
B+-A−	−2.6399	−4.7633	−0.5166	0.0102	**Significant**
B−-A+	−0.9606	−3.0839	1.1627	0.6155	Not significant
B+-A+	−1.9073	−4.0307	0.2161	0.0909	Not significant
B+-B−	−0.9467	−3.0701	1.1767	0.6264	Not significant

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