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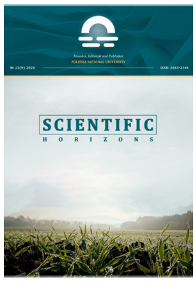

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Potential of leguminous crops for sustainable development of the agricultural sector

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Abstract. The purpose of the present study was to determine the agro-ecological advantages of growing leguminous crops compared to conventional cereals, particularly their impact on soil quality, biological activity, and productivity of agro-ecosystems. The study investigated the impact of leguminous crops – peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) – on soil physicochemical properties, microbiological composition, biological nitrogen fixation, yield and stability of agroecosystems in the arid conditions of southern Ukraine. The study was conducted in comparison with control plots sown with wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), which allowed assessing the effectiveness of leguminous crops in improving soil fertility and their contribution to maintaining agroecosystem sustainability. The results showed that the cultivation of leguminous crops contributed to an increase in humus content, increased soil capillary porosity, and improved water retention

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properties, while these indicators stayed lower in the control plots with cereals. The study also recorded a significant increase in the number of nitrogen-fixing (*Bradyrhizobium, Azotobacter*) and phosphorus-mobilising (*Pseudomonas, Bacillus*) bacteria in the plots with leguminous crops, which indicated an increase in biological processes in the soil. Yields of wheat and barley were dependent on the level of mineral nutrition, while leguminous crops provided a stable level of productivity without additional nitrogen fertilisation. The findings confirmed the feasibility of integrating leguminous crops into crop rotations to maintain soil fertility, improve microbiological balance, and reduce dependence on mineral fertilisers. It was found that biological nitrogen fixation by peas, lentils, and beans increases the level of available nitrogen in the soil, which positively influences the productivity of agroecosystems compared to conventional cereals

Keywords: fertility; nitrogen fixation; organic recovery; environmental sustainability; microbiological activity

INTRODUCTION

The relevance of the present study was driven by the growing need for sustainable development of the agricultural sector and rational use of natural resources. The intensification of agriculture is accompanied by gradual soil depletion, decreasing humus levels, degradation of agroecosystems, and increased dependence on mineral fertilisers. Leguminous crops such as peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) play an essential role in maintaining soil fertility due to their ability to biologically fix nitrogen, improve soil structure, increase water retention capacity, and enhance microbiological processes. The cultivation of these crops helps to reduce the use of mineral nitrogen fertilisers, which reduces the environmental burden on agroecosystems (Tereshchenko & Tarabrina, 2025).

The research problem is related to the need to develop effective agricultural technologies that will reduce the negative impact of intensive farming on the environment. Conventional farming methods cause excessive use of mineral fertilisers, which leads to soil acidification, nutrient imbalances, and a decrease in biodiversity. One solution to this problem is to integrate leguminous crops into crop rotations, which will contribute to the natural enrichment of soil with nitrogen, improve its structural properties, and reduce the need for synthetic fertilisers. The study of the impact of peas, lentils, and beans on agroecosystems allows assessing their contribution to maintaining ecological balance, increasing the yield of subsequent crops, and improving soil biological activity (Panfilova *et al.*, 2023). According to V.A. Mazur *et al.* (2021), modern cultivation technologies for leguminous crops contribute to an increase in the level of humus and biological activity of the soil, which improves its water-holding capacity and reduces the risk of degradation. According to A. Movchaniuk (2021), the integration of leguminous crops into crop rotations can reduce the need for nitrogen fertilisers by up to 40%, which reduces the financial burden on agricultural producers. According to I.V. Tomashuk and R.O. Horobchuk (2024), the use of leguminous crops in crop rotations increases the yield of subsequent crops by 15%-20%, which is explained by the improvement of soil structure and its enrichment with nitrogen. As proven by R.D. Semba *et al.* (2021), leguminous crops contain 20%-28% protein and a significant amount of micronutrients, making them a valuable element of food security.

As confirmed by the findings of M.M. Rahman *et al.* (2022), growing leguminous crops helps reduce greenhouse gas emissions and improves the water balance of agroecosystems, which is a crucial factor in climate change adaptation. According to L. Ditzler *et al.* (2021), leguminous crops help to increase the number of beneficial soil microorganisms and reduce erosion by 15%-20%, which positive influences soil fertility. According to H. Ferreira *et al.* (2021), leguminous crops are a key element of sustainable agriculture, as biological nitrogen fixation reduces the need for mineral fertilisers and reduces the environmental burden of the agricultural sector. As K.R. Ramya *et al.* (2022) emphasised, pigeon pea (*Lathyrus sativus*) has a particular potential, as it is characterised by high nutritional value and resistance to drought conditions.

According to M.A. Uebersax *et al.* (2023), dry beans (*Phaseolus vulgaris* L.) are an essential element of sustainable agricultural production due to their high protein content and ability to improve soil characteristics. As confirmed by the findings of E. Kebede (2021), biological nitrogen fixation by leguminous crops reduces the need for fertilisers and improves soil quality. According to J. Jena *et al.* (2022), leguminous crops increase biodiversity, water balance, and prevent the degradation of arable land, making them a vital component of sustainable agricultural technologies. According to G. Cusworth *et al.* (2021a), the massive adoption of leguminous crops in Europe will help reduce the impact of the agricultural sector on climate change and develop sustainable food systems. The analysis of studies confirmed that leguminous crops play an essential role in maintaining soil fertility, improving environmental sustainability and food security. The purpose of this study was to assess the influence of growing peas, lentils, and beans on soil physicochemical properties, biological nitrogen fixation, soil microbiological composition, yields, and stability of agroecosystems in the arid conditions of southern Ukraine. The principal objectives of the study were to determine the impact of peas, lentils, and beans on soil physicochemical properties and microbiological composition, to assess the efficiency of biological nitrogen fixation and its contribution to soil fertility, and to analyse the yield of these crops in comparison with wheat and barley.

MATERIALS AND METHODS

The study was conducted in April-October 2024 at the National Research and Production Centre of Mykolaiv National Agrarian University in Mykolaiv region, southern Ukraine. The experimental plots were located in the steppe zone on ordinary black soil with a total area of 2 ha. The climatic conditions of the study area were characterised by high average annual temperatures, precipitation deficit, and frequent dry periods, which allowed assessing the resistance of leguminous crops to stress factors and their influence on the stability of agroecosystems. The object of the study was leguminous crops, namely peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*), which were grown from May to August, as well as control crops – wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), which were sown in April. The key aspects of the study included soil physicochemical parameters, the impact of biological nitrogen fixation, changes in soil microbiological composition, yield, and agronomic characteristics of leguminous and cereal crops, and the impact of leguminous crops on agroecosystem stability.

The study was conducted on two plots: a control plot and an experimental plot. The control plot was sown with wheat and barley grown in a conventional way without biostimulants. The experimental plot included peas, lentils, and beans, which were actively biologically fixed with nitrogen. To increase productivity, mineral fertilisers were applied to the control plot: ammonium nitrate (N_{34}) at a dose of 90 kg/ha and superphosphate (P_2O_{546}) at a dose of 60 kg/ha. No mineral fertilisers were applied on the experimental plot, which allowed assessing the effectiveness of biological nitrogen fixation and improvement of soil characteristics under the influence of leguminous crops. The physicochemical parameters of the soil were analysed according to the following parameters: acidity (pH), humus content, macro- and microelements, soil density, moisture, capillary porosity, water permeability, and nitrate and ammonium nitrogen content. Acidity was measured using a Hanna HI 98130 pH meter. The humus content was estimated by the Turin method, while macro- and microelements were determined by spectrophotometric method (Shimadzu UV-1800). The content of total nitrogen was estimated by the Kjeldahl method, while nitrate and ammonium nitrogen – by ion-selective electrodes (Bremner, 1960). Soil density was determined by the ring sample method, moisture content – by the gravimetric drying method, capillary porosity – by the laboratory permeability method, and soil erosion resistance – by the Savvinov method (DSTU No. 4138-2002, 2002).

The effect of biological nitrogen fixation was determined by analysing the activity of nodule bacteria (*Rhizobium leguminosarum*), the number of which was estimated by the method of serial dilutions. The level of accumulation of available nitrogen in the soil was studied, specifically, the content of mineral, organic, and available nitrogen in the soil solution. The determination was carried out using the spectrophotometric method and the Kjeldahl method. The study also analysed the activity of nitrogenase, which is a key indicator of the efficiency of biological nitrogen fixation, using the acetylene reduction method. The ammonium nitrogen content was determined by the colorimetric method, and the nitrate nitrogen content was determined by ion-selective electrodes. The nitrogen balance in the plant-soil system was also assessed by determining the nitrogen utilisation factor. Changes in the microbiological composition of the soil were assessed according to the number of nitrogen-fixing bacteria (*Bradyrhizobium, Azotobacter*), phosphorus-mobilising bacteria (*Pseudomonas, Bacillus*), and the total number of soil microorganisms. The analysis was performed using the colony forming units (CFU/g soil) method. The detection of changes in the microbiological composition helped to assess the impact of leguminous crops on the activation of beneficial microflora and the improvement of soil biological activity.

Yields and agronomic characteristics of leguminous and cereal crops were assessed by measuring average yield (t/ha), thousand-kernel-weight, protein content in grain, starch content, germination energy and field germination, plant height, leaf area, number of productive stems, and plant biomass. The yield was determined by direct weighing of the grain after harvest. Protein content was analysed by the Kjeldahl method. Starch content was determined by the polarimetric method. The thousand-kernel-weight was measured on a RADWAG AS 220.R2 analytical balance. Field germination was evaluated according to the standard methods of DSTU No. 4138-2002 (2002). Morphological parameters of plants, such as height, leaf area, and number of productive stems, were determined using a Mitutoyo IP54 calliper and an electronic leaf area meter. The biomass was determined by weighing the dry matter after drying in a thermostat at 105°C. Drought tolerance was assessed on a 10-point scale, where 1 point corresponded to very low tolerance and 10 points – to complete tolerance to drought conditions. The evaluation was carried out by determining the relative water loss in the leaves, as well as by visual criteria – the degree of wilting and inhibition of plant growth during drought. Disease resistance was also determined on a 10-point scale, where 1 point indicated complete instability of the crop, and 10 points – high resistance to major pathogens. Disease diagnostics was carried out by visual monitoring of plants and identification of lesions according to the method of phytopathological analysis.

The impact of pulses on the stability of the agroecosystem was assessed by analysing soil erosion resistance, capillary porosity, biological activity, and the overall balance of organic matter. Erosion resistance was determined by the level of water resistance of soil aggregates using the Savvinov method (DSTU No. 4744:2007, 2007), and capillary porosity was determined by the laboratory permeability method (Richards, 1954). The biological activity of the soil was assessed by the level of respiratory activity of microorganisms using the Bazir method, and the total balance of organic matter was determined by the content of humus and total nitrogen (Anderson & Domsch, 1978). Statistical processing of the data was performed using Statistica 12 software (StatSoft, Inc.). To determine the reliability of the differences between the control and experimental parameters, the methods of analysis of variance (ANOVA) and Student's t-test ($p < 0.05$) were used. The statistical analysis helped to assess the efficiency of biological nitrogen fixation by leguminous crops, their influence on changes in physical, chemical, and microbiological parameters of the soil, as well as the significance of these changes for the stability of the agroecosystem and improvement of crop yields. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS

Physical and chemical characteristics of the soil. The soil pH analysis showed that in the control plots (wheat, barley) the acidity stayed within 5.5-6 pH, while in the experimental plots sown with peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*), it increased to pH 6.2-6.8. This indicated a decrease in soil acidity during the cultivation of leguminous crops. The key factor that influenced this indicator was the biological fixation of nitrogen by nodule bacteria, which reduced the need for mineral fertilisers that cause acidification. The humus content in the experimental plots with peas, lentils, and beans increased by 0.4%-0.6%, while in the control plots it stayed stable (2.4%-2.8%). This increase was explained by the high biomass of leguminous crop root residues, which contributed to the accumulation of organic matter and its transformation into stable humus compounds. The assessment of the soil structure showed that the share of agronomically valuable aggregates (0.25-10 mm) in the control plots was 65%-70%, while in the experimental plots with peas, lentils, and beans this figure increased to 77%-83%. This indicated an improvement in the aggregate structure of the soil, which contributed to a reduction in soil compaction, improved water permeability, and increased erosion resistance.

The study of soil water permeability showed that in the control plots this indicator fluctuated between 10-15 mm/h, while in the experimental plots it increased to 13-20 mm/h (an increase of 25%-30%). This indicates a decrease in surface water runoff, which is a significant factor for preserving soil moisture and preventing erosion processes. Soil density indicators confirmed that the cultivation of peas, lentils, and beans contributed to a reduction in soil compaction. In the control plots, the soil density was 1.3-1.45 g/cm^3, while in the experimental plots it was 1.1-1.3 g/cm^3. This meant that leguminous crops improved soil aeration and water permeability, which is critical for the development of the plant root system. The analysis of nitrogen content showed that in the control plots its concentration was 0.12%-0.16%, while in the experimental plots sown with peas, lentils, and beans it was 0.18%-0.22%, which meant an increase of 30%-40%. This proved the effectiveness of symbiotic nitrogen fixation, which accumulated available nitrogen in the soil, reducing the need for nitrogen fertilisers.

The phosphorus content in the control plots was 18-25 mg/kg, while in the plots with peas, lentils, and beans it was 24-32 mg/kg, an increase of 20%-28%. The potassium content increased by 10%-20% (180-220 mg/kg in the control plots versus 220-260 mg/kg in the experimental plots). The increased concentration of phosphorus and potassium in the experimental samples indicated the activation of microbiological processes that contributed to the mobilisation of these elements from soil reserves and improved their availability to plants. The study of the organic carbon content showed that its concentration in the control plots was 1.8%-2.2%, while in the plots with peas, lentils, and beans it increased to 2.4%-2.8% (an increase of 30%-35%). This indicated an improved accumulation of organic matter and higher biological activity of the soil, which contributed to the stabilisation of its fertility. The assessment of soil capillary porosity showed that its level in the control plots was 42%-48%, while in the plots with peas, lentils, and beans this figure reached 50%-57% (an increase of 8%-12%). This meant that the experimental plots retained moisture better, which positively influenced the water balance and ensured stable conditions for plant growth (Table 1).

***Table 1**. Physical and chemical characteristics of the soil*

Indicator	Control (grain crops, 2024)	Leguminous crops (experimental plots, 2024)	Change (%)	Months of research
soil pH (hydrogen index, characterises the acidity or alkalinity of the soil)	5.5-6 (wheat, barley)	6.2-6.8 (peas, lentils, beans)	+0.5-0.8	May-August

Table 1. Continued

Indicator	Control (grain crops, 2024)	Leguminous crops (experimental plots, 2024)	Change (%)	Months of research
Humus content (%)	2.4-2.8 (wheat, barley)	2.8-3.4 (peas, lentils, beans)	+0.4-0.6	May-August
Agronomically valuable aggregates (%)	65-70 (wheat, barley)	77-83 (peas, lentils, beans)	+12-18	May-August
Water permeability (mm/h)	10-15 (wheat, barley)	13-20 (peas, lentils, beans)	+25-30	May-August
Soil density (g/cm3)	1.3-1.45 (wheat, barley)	1.1-1.3 (peas, lentils, beans)	-0.1-0.2	May-August
Nitrogen content (%)	0.12-0.16 (wheat, barley)	0.18-0.22 (peas, lentils, beans)	+30-40	May-August
Phosphorus content (mg/kg)	18-25 (wheat, barley)	24-32 (peas, lentils, beans)	+20-28	May-August
Potassium content (mg/kg)	180-220 (wheat, barley)	220-260 (peas, lentils, beans)	+10-20	May-August
Total organic carbon content (%)	1.8-2.2 (wheat, barley)	2.4-2.8 (peas, lentils, beans)	+30-35	May-August
Capillary soil porosity (%)	42-48 (wheat, barley)	50-57 (peas, lentils, beans)	+8-12	May-August

Source: *developed by the authors of this study*

Thus, the results of the 2024 study confirmed that peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) helped to reduce soil acidity, increase humus content, improve its structural stability, increase the concentration of macronutrients (nitrogen, phosphorus, potassium), and improve water holding capacity.

Impact of biological nitrogen fixation. The content of available nitrogen in the soil in the experimental plots was 30%-40% higher than in the control samples, which confirmed the effectiveness of symbiotic nitrogen fixation. In the control plots, its level was 0.12%-0.16%, while in the experimental plots it was 0.18%-0.22%. The high efficiency of biological nitrogen fixation was conditioned by the vigorous activity of nodule bacteria of the genus *Rhizobium*, which formed symbiotic relationships with leguminous crops, providing them with nitrogen without mineral fertilisers. Assessment of root system morphology showed a significant difference in the number of nodules between control and experimental plants. In wheat and barley, this figure did not exceed 5-10 nodules per plant, indicating low nitrogen fixation activity. At the same time, 60-100 nodules per plant were formed on the roots of peas, lentils, and beans, which confirmed their high ability to fix atmospheric nitrogen. An increase in the number of nodules by 900-1,100% compared to the control samples indicated the effectiveness of using leguminous crops to improve the nitrogen balance of the soil. The weight of nodules on the control crops was only 0.1-0.3 g/plant, suggesting their low activity in nitrogen fixation processes. However, in the experimental plots, the nodule weight varied between 1.2-2.5 g/plant, which meant an increase of 400-700%. This emphasised the value of peas, lentils, and beans as effective nitrogen fixers that can substantially increase the level of nitrogen in the soil.

Thanks to biological nitrogen fixation, the need for nitrogen fertilisers was reduced by up to 40%. This not only reduces the financial cost of nitrogen fertilisation, but also helps to reduce the environmental burden, as excess mineral nitrogen can cause water pollution. Increased nitrogen levels directly affected the yield of subsequent crops in the rotation. Control plots with wheat or barley as a predecessor yielded 4.5-5 t/ha of wheat and 3.8-4.2 t/ha of barley. At the same time, in the experimental plots, wheat yields increased to 5.2-6 t/ha and barley yields to 4.2-5 t/ha, which indicated a 15%-20% increase in productivity. Another significant consequence of effective nitrogen fixation was a reduction in nitrogen leaching into groundwater. On the control plots, the leaching level was 2.5-3 mg/L, which is an indicator of extensive nitrogen losses due to leaching. In the experimental plots, where nitrogen fixation occurred naturally, this figure dropped to 1.2-1.5 mg/l (a 40%-50% reduction). This means that nitrogen fixed in a biological form is better retained in the soil and continues to be available to plants for a long time. The number of beneficial microflorae, including nitrogen-fixing bacteria and microorganisms involved in the transformation of organic nitrogen, also increased pronouncedly. In the control plots, the number of soil microorganisms was 1.8×10^6 CFU/g soil, while in the experimental plots it was 3.5×10^6 CFU/g soil, which indicated an increase in microbiological activity by 90-100%. This contributed to more intensive decomposition of organic matter and increased overall soil fertility.

The increase in nitrogen levels also positively influenced humus content. In the control plots, the humus content stayed at 0.2%-0.3%, while in the experimental plots it increased to 0.4%-0.6% (an increase of 100-200%). This indicated an improvement in the structure of organic matter in the soil and an increase in its stability, which contributed to the long-term preservation of fertility. The physical characteristics of the soil also changed as a result of biological nitrogen fixation. The cultivation of leguminous crops contributed to a decrease in soil density from 1.3-1.45 g/cm^3 in the control plots to 1.1-1.3 g/cm^3 in the experimental plots, which indicated a 10-12% reduction in compaction. This improved water permeability and air permeability, which contributed to the development of the root system of plants and increased the efficiency of nutrient absorption (Table 2).

***Table 2**. Impact of biological nitrogen fixation*

Indicator	Control (wheat, barley)	Experiment (peas, lentils, beans)	Change (%)
Available nitrogen in the soil (%)	0.12-0.16	0.18-0.22	+30-40
Number of nodules on the roots (pcs./plant)	5-10	60-100	+900-1,100
Total nodule weight (g/plant)	0.1-0.3	1.2-2.5	+400-700
Reduced demand for nitrogen fertilisers (%)	0	Up to 40	Reduced costs
Post-crop wheat yield (t/ha)	4.5-5	5.2-6	+15-20
Post-crop barley yield (t/ha)	3.8-4.2	4.2-5	+12-18
Nitrogen leaching into groundwater (mg/l)	2.5-3	1.2-1.5	-40-50
Number of soil microorganisms (CFU/g soil)	1.8×10^6	3.5×10^6	+90-100
Increase in humus level (%)	0.2-0.3	0.4-0.6	+100-200
Reduced soil compaction (g/cm^3)	1.3-1.45	1.1-1.3	-10-12

***Source:** developed by the authors of this study*

The obtained results confirmed the high efficiency of biological nitrogen fixation with peas, lentils, and beans. Not only does it increase the level of available nitrogen in the soil, but it also improves its microbiological properties, reduces the need for mineral fertilisers, and contributes to the environmental sustainability of agricultural systems. The use of these crops in crop rotation is an effective measure to preserve and improve soil fertility, optimise agricultural technologies, and increase yields of subsequent crops.

Changes in the microbiological composition of the soil. On the control plots, the number of nitrogen-fixing bacteria (*Rhizobium leguminosarum*, *Bradyrhizobium japonicum*, *Sinorhizobium meliloti*) was 2.1×10^6 CFU/g soil, which indicated a low natural activity of symbiotic processes. In the experimental plots, the number of these bacteria reached 4.8×10^6 CFU/g soil, which meant a 128% increase. Such a pronounced difference was explained by the fact that the root system of peas, lentils, and beans actively attracted nodule bacteria, which entered into symbiosis with plants and contributed to the biological fixation of atmospheric nitrogen. The number of phosphate-mobilising bacteria (*Pseudomonas fluorescens*, *Bacillus megaterium*, *Penicillium bilaii*) involved in the conversion of insoluble forms of phosphorus into those available to plants in the control plots was 1.5×10^6 CFU/g soil. In the experimental plots, this figure reached 3.2×10^6 CFU/g soil, which was an increase of 113%. This indicated that leguminous crops contributed to the activation of microorganisms capable of decomposing organophosphorus compounds and increasing the availability of phosphorus to plants, which is a vital factor for increasing yields.

The number of actinomycetes (*Streptomyces* spp., *Micromonospora* spp.), which play a major role in the decomposition of organic matter and the synthesis of biologically active compounds, was 0.8×10^6 CFU/g soil in the control plots. In the experimental plots, this figure doubled and reached 1.6×10^6 CFU/g soil, which confirmed a considerable improvement in the decomposition of organic matter. The high number of actinomycetes indicated the active formation of stable humus compounds in the soil. The study of the dynamics of fungi-reducers (*Trichoderma* spp., *Aspergillus* spp., *Fusarium oxysporum*) involved in the decomposition of complex organic matter and transformation of nutrients showed that in the control plots their number was 0.6×10^6 CFU/g soil. In the experimental plots, this figure increased to 1.2×10^6 CFU/g soil, indicating a doubling of the fungal biota activity. The total number of microorganisms in the soil also changed substantially. In the control plots, it was 4.5×10^6 CFU/g soil, while in the experimental plots it was 9.8×10^6 CFU/g soil, which was a 118% increase. This indicator confirmed that plant residues of peas, lentils, and beans stimulated the activation of microorganisms responsible for the decomposition of organic matter, which directly affected the increase in soil fertility (Fig. 1).

The results showed that the cultivation of peas, lentils, and beans contributed to the stabilisation of the soil microbial composition, an increase in the number of nitrogen-fixing and phosphate-solubilising bacteria, and an increase in overall biological activity. This ensured better availability of nutrients for plants and contributed to greater yields of subsequent crops in the rotation.

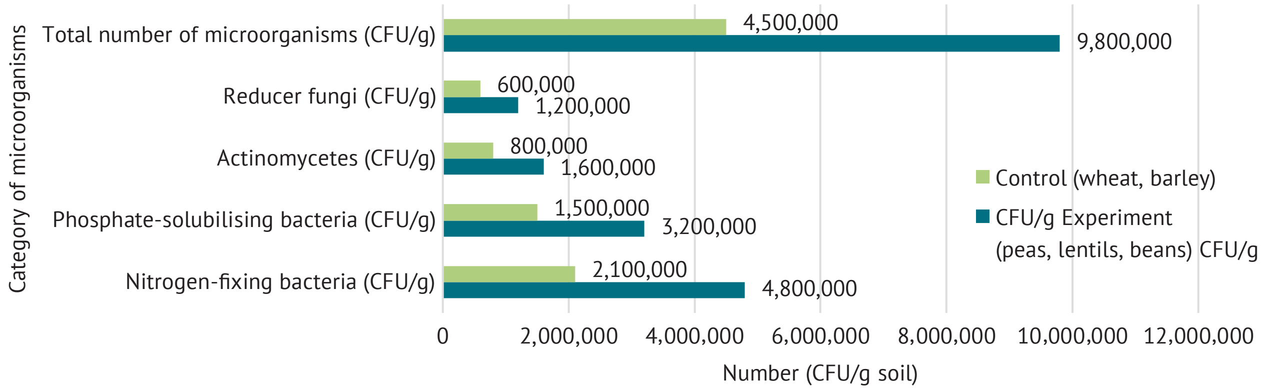

***Figure 1**. Changes in the microbiological composition of the soil*
***Source:** developed by the authors of this study*

Yields and agronomic characteristics of leguminous and grain crops. Average yields of grain crops were greater compared to leguminous crops. Wheat demonstrated the greatest yields (4-5.5 t/ha), while barley had yields within 3.5-4.8 t/ha. This was explained by the greater adaptability of cereals to different climatic conditions and their intensive selection. Among the leguminous crops, peas showed the greatest yields (2.8-3.5 t/ha), while lentils had the lowest yields (1.8-2.5 t/ha), which was explained by their sensitivity to moisture deficit and slow development in the early stages of the growing season. Plant height varied considerably between the crops under study. Wheat had the greatest height (80-110 cm), which contributed to its high competitiveness in closed crops. Barley had a height of 70-100 cm, which made it less vulnerable to lodging. Peas and beans were 60-85 cm and 50-70 cm tall, respectively, which allowed them to produce stable yields even under unfavourable conditions. Lentils were the shortest crop (40-55 cm), which limited their ability to compete effectively for light. The thousand-kernel-weight (TKW) was the highest for beans (250-350 g), which indicated the high energy value of its seeds. Peas had average TKW values (200-250 g), while lentils had the lowest TKW (30-45 g), making them a less energy-intensive crop. By comparison, wheat and barley had TKW values of 40-55 g and 45-60 g, respectively, which reflected their compact seed structure, which contributed to uniform maturation and reduced losses during harvesting.

The protein content of leguminous crops was significantly higher than that of grain crops. Lentils contained 24%-28% protein, making them a valuable crop for the production of vegetable protein concentrates. Peas had 22%-25% protein, while beans had 20%-23%, which also indicated their high nutritional value. In comparison, wheat and barley had 10%-14% and 9%-13% protein, respectively, confirming their primary function as a source of carbohydrates in the food industry. The vegetation period was the longest for wheat (210-230 days) and barley (180-200 days), which indicated that they needed a long development period to form a stable harvest. Among pulses, peas had the shortest growing season (85-100 days), making them the best crop for short-term crop rotations. Lentils had a vegetation period of 90-110 days, while beans had a vegetation period of 95-120 days, making them less adaptable to the conditions of a short vegetation period. Drought tolerance was highest in beans (9 points out of 10), which confirmed their ability to effectively use soil moisture. Peas had a strong level of resistance (8 points), while lentils showed 7 points, indicating their greater sensitivity to moisture deficit. Wheat and barley had scores of 6 and 7, respectively, indicating their relative resistance to drought, but lesser adaptability compared to leguminous crops. Disease resistance varied between crops. Lentils demonstrated the highest resistance (8 points), which confirmed their lower vulnerability to fungal and bacterial infections. Peas and wheat had analogous scores (7 points), making them relatively resistant crops. Beans and barley demonstrated the lowest level of resistance (6 points), which was explained by their tendency to develop bacterial and fungal diseases (Table 3).

***Table 3**. Yields and agronomic characteristics of leguminous and grain crops*

Parameter	Peas (Pisum sativum)	Lentils (Lens culinaris)	Beans (Phaseolus vulgaris)	Wheat (Triticum aestivum)	Barley (Hordeum vulgare)
Average yield (t/ha)	2.8-3.5	1.8-2.5	2.2-3	4-5.5	3.5-4.8
Plant height (cm)	60-85	40-55	50-70	80-110	70-100
Thousand-kernel weight (g)	200-250	30-45	250-350	40-55	45-60
Protein in seeds (%)	22-25	24-28	20-23	10-14	9-13

Table 3. Continued

Parameter	Peas (Pisum sativum)	Lentils (Lens culinaris)	Beans (Phaseolus vulgaris)	Wheat (Triticum aestivum)	Barley (Hordeum vulgare)
Vegetation period (days)	85-100	90-100	95-120	210-230	180-200
Resistance to drought (points, 1-10)	8	7	9	6	7
Disease resistance (points, 1-10)	7	8	6	7	6

Source: *developed by the authors of this study*

The results showed that leguminous crops are valuable elements of agricultural systems, as they not only provide high-quality protein products, but also contribute to soil fertility and crop stability in crop rotation. Compared to grain crops, they have lower yields but higher biological value due to their high protein content and ability to fix atmospheric nitrogen.

Impact of leguminous crops on agroecosystem stability. Improvement of soil structure accounted for 25% of the total impact, which confirmed the effectiveness of leguminous crops in improving the mechanical composition of the soil. This was explained by the high biomass of the root systems and an increase in the number of stable soil aggregates. Compared to the control plots, the content of agronomically valuable aggregates in the soil increased by 12%-18%, which reduced its tendency to compaction and improved water permeability. A 15% reduction in erosion was another prominent result of the use of leguminous crops. Improved soil structure and increased organic matter content contributed to a reduction in water and wind erosion. Better retention of moisture and organic material in the topsoil markedly reduced the risk of soil degradation. Moisture retention accounted for 20% of the overall impact of leguminous crops on the agroecosystem. The high porosity of the soil and the increased water-holding capacity contributed to reduced evaporation and better moisture accumulation in the topsoil. As a result, the capillary porosity in the experimental plots increased by 8%-12% compared to the control plots.

The increase in organic matter accounted for 18% of the total impact. The humus content in the experimental plots increased by 0.4%-0.6%, which confirmed the effectiveness of leguminous crops in improving the organic balance of the soil. The introduction of a significant amount of root and plant residues contributed to the improvement of humification processes, which positively influenced the biological activity and productivity of agroecosystems. The 12% increase in biodiversity was caused by improved conditions for the development of microbiota, beneficial insects, and soil fauna. The study of the number of microorganisms in the soil confirmed that their total number in the experimental plots increased by 118% compared to the control samples. Specifically, the number of nitrogen-fixing bacteria (*Rhizobium leguminosarum*, *Bradyrhizobium japonicum*) and phosphate-solubilising bacteria (*Pseudomonas fluorescens*, *Bacillus megaterium*) increased by 128% and 113%, respectively. Reduced fertiliser requirements accounted for 10% of the total impact. Thanks to the active biological nitrogen fixation, the need for mineral nitrogen fertilisers was reduced by up to 40%, which contributed to environmental safety and reduced financial costs for agricultural production. The improved absorption of phosphorus and potassium by microorganisms also reduced the need for phosphorus and potassium fertilisers (Fig. 2).

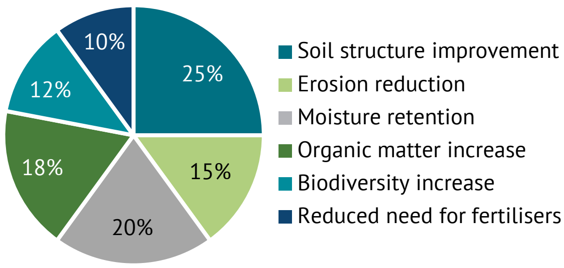

Figure 2*. Impact of leguminous crops on agroecosystem stability*
Source: *developed by the authors of this study*

The obtained results confirmed that the cultivation of leguminous crops contributed to increasing the sustainability of agroecosystems, reducing the negative impact of agricultural production on the environment and optimising biological processes in the soil. This demonstrated the valuable role of peas, lentils, and beans in maintaining ecological balance and increasing agricultural efficiency.

DISCUSSION

The results of the study confirmed the positive influence of leguminous crops on the agroecosystem. Compared to the control plots sown with wheat and barley, the experimental pea, lentil, and bean crops contributed to an increase in soil nitrogen content, which was explained by active biological nitrogen fixation by nodule bacteria. There was an improvement in the physical and chemical properties of the soil, including an increase in humus content and capillary porosity, which contributed to the improvement of water retention capacity. Microbiological analysis revealed an increase in the number of nitrogen-fixing and phosphorus-solubilising bacteria, which indicated the activation of beneficial microflora under the influence of leguminous crops. The yields of leguminous crops were stable, and their impact on the agroecosystem was manifested in the reduction of erosion processes and improvement of soil biological activity. These findings confirmed the effectiveness of growing leguminous crops to improve soil fertility and agroecosystem sustainability.

M.V. Conti *et al*. (2021) and U. Sahoo *et al*. (2023) confirmed that leguminous crops contributed to the improvement of the physical and chemical properties of the soil through the accumulation of organic compounds and increased activity of soil microflora. Biological nitrogen fixation by leguminous crops was shown to reduce the use of mineral fertilisers, which positively influenced soil structure and fertility. Another significant factor is the improvement of the soil's water-holding capacity, which is crucial in arid regions (Laposha *et al*., 2020; Zymaroieva *et al*., 2021). The findings obtained are consistent with the present study, which observed an increase in humus content and activation of nitrogen fixation processes. However, unlike these studies, the present study assessed the direct influence of individual leguminous crops without intercropping, which allowed for more accurate data on soil changes. G. Cusworth *et al*. (2021b) and A. Raihan *et al*. (2024) confirmed that the inclusion of leguminous crops in crop rotation improves the sustainability of the agroecosystem by increasing the microbiological activity of the soil and reducing dependence on chemical fertilisers. These studies showed that leguminous crops increase the number of nitrogen-fixing and phosphorus-solubilising bacteria, which improves plant nutrient uptake. These findings were confirmed by the present study, which also recorded an increase in the activity of microbial groups in the soil in experimental plots with peas, lentils, and beans. However, unlike the cited studies, the present study analysed not only the impact of leguminous crops on microbiological parameters, but also the relationship between these changes and crop productivity, which allows for a comprehensive assessment of their agroecological effect.

According to S. Kuyah *et al*. (2021) and M. Ahmed *et al*. (2022), the use of leguminous crops in agriculture contributed to the improvement of soil quality by increasing the level of organic matter and improving its physical and chemical properties. Leguminous crops were shown to markedly reduce the dependence on mineral fertilisers due to their high nitrogen fixing capacity, which contributed to improved soil quality. Furthermore, the study confirmed that in the context of climate change, the use of leguminous crops in crop rotations reduced the risk of soil degradation and helped to maintain soil fertility in the long term. The present study was consistent with these findings, as it was found that the cultivation of peas, lentils, and beans positively influenced humus levels, soil capillary porosity, and biological activity. However, unlike the study by M. Ahmed *et al*., the present study focused on concrete regional characteristics, which enabled more applied conclusions on the effectiveness of leguminous crops in southern Ukraine. As shown by K. Singh *et al*. (2021) and K. Jones *et al*. (2023), the active interaction of leguminous crops with symbiotic bacteria helped to improve the nitrogen balance of the soil and ensured more efficient absorption of macro- and microelements. It was found that an increase in the number of nitrogen-fixing bacteria of the genus *Rhizobium* and phosphorus-solubilising microorganisms contributed not only to the improvement of the physical and chemical properties of the soil, but also to an increase in the yield of leguminous crops. This study also recorded an analogous trend – the number of beneficial microorganisms increased in the experimental plots with peas, lentils and beans, which positively impacted the agroecosystem. However, unlike these studies, the present study considered not only the overall impact of microorganisms, but also the concrete effects of certain types of leguminous crops on the microbiological composition of the soil, which helped to obtain practical recommendations for their use in regions with an arid climate.

According to the findings of S. Kumar *et al*. (2022) and A. Nord *et al*. (2022), the cultivation of leguminous crops greatly affected food security and nutrition, while also contributing to improved soil fertility through biological nitrogen fixation. Leguminous crops were found to improve diets through their high protein, vitamin, and micronutrient content, and to positively influence soil fertility through biological nitrogen fixation. However, in some regions, insufficient adoption of agricultural technologies and low adaptation to specific climatic conditions continued to be limiting factors (Kiurchev *et al*., 2020; Didur *et al*., 2023). The present study confirmed the positive impact of leguminous crops on improving soil characteristics and yields but focused on assessing the effectiveness of distinct types of leguminous crops in a regional perspective. This allowed drawing conclusions on their adaptation to the arid conditions of southern Ukraine and identifying the most effective crops for restoring soil fertility. As emphasised by B. Balázs *et al*. (2021) and K.Y. Belachew *et al*. (2022), the use of leguminous crops in agricultural systems contributed to increasing the productivity of agri-food complexes and reducing the yield gap between different regions. It was found that the integration of leguminous crops into modern agricultural technologies could substantially increase production efficiency by improving soil structure and reducing dependence on mineral fertilisers. The study also confirmed that different leguminous crops showed uneven yields depending on local climatic and agronomic conditions. The present study also found pronounced differences between pea, lentil, and bean yields depending on soil type and moisture levels. However, unlike the above studies, the present study assessed not only the yield potential of crops, but also their impact on the stability of the agroecosystem, which enabled a comprehensive assessment of their environmental performance.

According to S.K. Upa- dhyay *et al*. (2023) and K. Dave *et al*. (2024), climate change considerably affected the growth and productivity of leguminous crops, which required the use of adaptive technologies to maintain their yields. It was proved that rising temperatures and changes in precipitation patterns considerably affected the growth and productivity of leguminous crops, which required adaptive approaches to their cultivation. The use of rhizobacteria, which can stimulate plant growth, proved to be an effective way to maintain the productivity of leguminous crops under climate change (Kyselov, 2024). The present study confirmed that leguminous crops helped improve the microbiological composition of the soil by activating nitrogen-fixing and phosphorus-solubilising bacteria, which positively influenced soil fertility. However, in contrast to these studies, the present study focused on the direct impact of various leguminous crops on soil indicators and their potential for use in arid regions. According to M.F. Desire *et al*. (2021) and S. Kumari and S.K. Maiti (2022), cultivation of leguminous crops played a valuable role in improving soil fertility and ensuring food security. The researchers found that biological nitrogen fixation not only contributed to soil enrichment with nutrients but also provided the possibility of reclaiming degraded land. Additionally, these studies proved that leguminous crops can be an effective source of micronutrients and protein, which made them promising for food fortification in nutrient-poor regions. The results obtained in the present study generally supported these findings, as they also revealed positive effects of leguminous crops on humus content and soil structure. At the same time, unlike S. Kumari *et al*. and M.F. Desire *et al.*, the present study focused on determining the concrete influence of each leguminous crop on individual soil parameters, which helped to obtain a more detailed picture of their effectiveness in the conditions of southern Ukraine.

As confirmed by K. Kumara *et al*. (2023) and J.R. Lamichhane *et al*. (2023), the introduction of leguminous crops into crop rotations contributed to a marked increase in the carbon balance of agroecosystems and improved the overall environmental sustainability of agricultural land. The use of leguminous crops in farming systems was shown to increase the organic carbon content of the soil, which reduced degradation and improved its water-retaining properties. Furthermore, studies showed that the use of relay-cropping methods with leguminous crops improved the use of soil resources and increased the efficiency of agroecosystems. The findings of the present study were consistent with these conclusions, as it was confirmed that the physical and chemical characteristics of the soil improved, the level of microbiological activity increased, and yields increased. However, unlike these studies, the present study analysed distinct types of leguminous crops in greater detail, which allowed assessing their adaptive efficiency in the face of climate change and draw practical conclusions regarding their use to restore soil fertility in arid regions. The findings confirmed the general conclusions of previous studies on the positive impact of leguminous crops on soil fertility, yields, and the stability of agroecosystems, specifically through biological nitrogen fixation and improved soil microbiological composition.

CONCLUSIONS

The study analysed the impact of growing leguminous crops on the key agroecological indicators of the soil and the productivity of agroecosystems in arid conditions. Peas, lentils, and beans were found to not only improve the physical and chemical properties of the soil, but also activate microbiological processes, which ensures their role in maintaining the stability of agricultural landscapes. Changes in the physical and chemical parameters of the soil confirmed the improvement of its structure in the experimental plots. Increased humus levels and improved capillary porosity contributed to effective moisture retention, which is a key factor in arid regions. This suggested that leguminous crops can play a valuable role in improving soil water management and preventing soil degradation. The study revealed a marked increase in the number of nitrogen-fixing and phosphorus-solubilising bacteria in the soil, which confirmed its biological activation under the influence of leguminous crops. Nitrogen uptake improved, reducing the need for mineral fertilisers. This is an essential environmental and economic factor that can help reduce the cost of agrochemicals and increase the environmental sustainability of agroecosystems. A comparative analysis of yields revealed that leguminous crops demonstrated a stable level of productivity regardless of moisture supply, while wheat and barley were significantly dependent on mineral nutrition. This indicated a greater adaptability of leguminous crops to stressful conditions, which can be a crucial factor in planning crop rotations in regions with a changing climate. The findings confirmed the prospects of leguminous crops for maintaining soil fertility, increasing its biological activity, and reducing dependence on mineral fertilisers. The cultivation of peas, lentils, and beans can play a key role in sustainable farming strategies, contributing to the long-term conservation of soil resources and increasing the environmental sustainability of agro-systems in arid conditions. A limitation of the study was that it was conducted within a single region with an arid climate, which may affect the generalisability of the findings to other agroclimatic zones. Further research should be aimed at assessing the long-term impact of leguminous crops on soil characteristics and their efficiency in different crop rotation systems and climatic conditions.

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Потенціал зернобобових культур для сталого розвитку аграрної галузі

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Анотація. Метою дослідження було визначити агроекологічні переваги вирощування зернобобових культур у порівнянні з традиційними зерновими, зокрема їхній вплив на якість ґрунту, біологічну активність та продуктивність агроекосистем. У статті досліджено вплив зернобобових культур – гороху (*Pisum sativum*), сочевиці (*Lens culinaris*) та квасолі (*Phaseolus vulgaris*) – на фізико-хімічні властивості ґрунту, мікробіологічний склад, біологічну фіксацію азоту, урожайність та стабільність агроекосистем у посушливих умовах Півдня України. Дослідження проводилося у порівнянні з контрольними ділянками, засіяними пшеницею (*Triticum aestivum*) та ячменем (*Hordeum vulgare*), що дозволило оцінити ефективність зернобобових у покращенні родючості ґрунту та їхній внесок у підтримку стійкості агросистем. Результати показали, що вирощування зернобобових сприяло збільшенню вмісту гумусу, підвищенню капілярної пористості ґрунту та покращенню його водоутримувальних властивостей, тоді як на контрольних ділянках зі злаковими культурами ці показники залишалися нижчими. Також було зафіксовано значне зростання чисельності азотфіксувальних (*Bradyrhizobium, Azotobacter*) та фосформобілізуючих (*Pseudomonas, Bacillus*) бактерій на ділянках із зернобобовими, що свідчило про активізацію біологічних процесів у ґрунті. Урожайність пшениці та ячменю виявилася залежною від рівня мінерального живлення, тоді як зернобобові забезпечували стабільний рівень продуктивності без додаткового внесення азотних добрив. Отримані результати підтверджують доцільність інтеграції зернобобових у сівозміни для підтримки родючості ґрунтів, покращення мікробіологічного балансу та зниження залежності від мінеральних добрив. Встановлено, що біологічна фіксація азоту горохом, сочевицею та квасолею забезпечує підвищення рівня доступного азоту в ґрунті, що позитивно впливає на продуктивність агроекосистем у порівнянні з традиційними зерновими культурами

Ключові слова: родючість; азотфіксація; органічне відновлення; екологічна стійкість; мікробіологічна активність