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Abstract

Background: The declining availability of traditional organic fertilizers and the need for sustainable waste management solutions have sparked interest in alternative nutrient sources for agriculture. This study investigates the potential of sewage sludge-based biofertilizers in hazelnut (Corylus avellana L.) cultivation, addressing both agricultural productivity and environmental concerns.

Objective: To evaluate and compare the effects of sewage sludge-based biofertilizers with traditional organic fertilizers on soil agrochemical properties and assess their environmental safety in hazelnut plantations in the Southern Steppe of Ukraine.

Methods: A two-year field experiment (2021-2022) was conducted, comparing six treatments: control (no fertilizer), cattle manure, chicken manure, two formulations of sewage sludge-based biofertilizers, and pure sewage sludge. Soil samples were analyzed for easily hydrolyzable nitrogen, mobile phosphorus and potassium, organic matter content, and ecotoxicity. Advanced statistical analyses, including ANOVA, Tukey's post-hoc tests, paired t-tests, and correlation analyses, were employed to assess treatment effects and temporal changes.

Results: Statistically significant differences were observed between fertilizer treatments for all major nutrients ($p < 0.05$). Sewage sludge-based Biofertilizer No. 1 demonstrated superior performance in increasing soil phosphorus content compared to traditional organic fertilizers (306.30 mg/kg vs. 174.75 mg/kg for cattle manure, $p < 0.05$). All organic fertilizers, including biofertilizers, significantly improved soil nitrogen content over the two-year period ($p < 0.05$). Potassium levels showed a significant increase (13.41% year-over-year, $p < 0.05$), while changes in nitrogen and phosphorus levels suggested positive trends but did not reach statistical significance. Importantly, ecotoxicity levels remained low ($E < 1.5$) across all treatments, indicating minimal short-term environmental risk.

Conclusions: This study provides compelling evidence for the potential of sewage sludge-based biofertilizers as effective and environmentally safe alternatives to traditional organic fertilizers in hazelnut cultivation. The findings have significant implications for sustainable agriculture, waste management, and circular economy practices. However, long-term studies are recommended to fully assess the cumulative effects on soil health, crop productivity, and potential contaminant accumulation. This research contributes to the development of innovative, sustainable fertilization strategies that can address both agricultural productivity and environmental conservation needs.

Keywords: biofertilizers, sewage sludge, soil fertility, hazelnut cultivation, sustainable agriculture, circular economy, ecotoxicity

This document is a study of a new approach, new assessment, new statistical inference, and new conclusions from the published research by Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128.

This sentence provides context for the document, explaining that it presents a novel analysis and interpretation of the research published by Nikipelova, O., Pyliak, N., & Hodorchuk, V. in 2024 on the use of organic fertilizers to increase hazelnut yield.

1. Introduction

The growing demand for food, coupled with the necessity to protect the natural environment, presents modern agriculture with a series of challenges. One of the key aspects of sustainable agricultural production is maintaining and improving soil fertility, which is particularly important in the context of climate change and agricultural intensification. In this light, the search for alternative sources of organic fertilizers becomes not only an economic issue but also an ecological one.

The cultivation of hazelnut (Corylus avellana L.) in Ukraine is gaining importance due to the growing market demand and favorable soil and climatic conditions in some regions of the country. However, to fully exploit the potential of this crop, it is necessary to ensure an adequate level of soil fertility, which poses a challenge in the face of decreasing availability of traditional organic fertilizers such as manure.

In recent years, increasing attention has been paid to the possibility of using alternative sources of organic matter, including sewage sludge, as potential fertilizers. Research on their application in agriculture aims not only to improve soil properties and crop yields but also to solve the problem of waste management in urban areas.

This study focuses on assessing the impact of various types of organic fertilizers, including innovative biofertilizers based on sewage sludge, on the agrochemical properties of soil in hazelnut cultivation in the conditions of the Southern Steppe of Ukraine. Particular attention was paid to analyzing the content of available forms of nitrogen, phosphorus, and potassium, as well as organic matter in the soil, and assessing the potential ecotoxicological risk associated with the use of these fertilizers.

The aim of the research was not only to determine the effectiveness of various organic fertilizers in improving soil fertility but also to assess the possibility of using sewage sludge as a safe and effective source of nutrients for plants. The results of these studies may have significant implications for the development of sustainable agricultural practices, waste management, and protection of soil resources in the context of changing climatic conditions and increasing pressure on the natural environment. The current state of the Ukrainian economy is marked by significant challenges, particularly in the realm of food security. The ongoing conflict and its repercussions have exacerbated existing issues, necessitating a comprehensive approach to improving the agricultural sector and ensuring the availability of essential food products. The demand for plant products in Ukraine is not fully satisfied, which underscores the urgency of exploring new sources of raw materials and enhancing the utilization of existing agricultural resources (Podsokha, 2023). Among the promising candidates for addressing these challenges is the hazelnut, specifically the species Corylus domestica, which has shown potential for cultivation in various regions of Ukraine (Blikhar, 2023).

The climatic and soil conditions in Ukraine are conducive to the growth of hazelnuts. The adaptability of hazelnut cultivation to the Ukrainian environment is supported by the favorable temperature and photoperiod, which are critical for the successful development of this nut-bearing plant. The integration of agrotechnical measures, such as proper pruning and nutrient management, can further enhance the yield and quality of hazelnut production. This aligns with the findings of research that emphasize that specific climatic conditions and soil nutrient content significantly influence agricultural outputs (Specific features of government regulation of ukraine’s agriculture sector within martial law, 2023). The potential for hazelnut cultivation not only addresses food security concerns but also contributes to the diversification of agricultural products in Ukraine, thereby enhancing the resilience of the agricultural sector.

The impact of the ongoing war on food security cannot be overstated. The conflict has disrupted traditional agricultural practices and supply chains, leading to increased food prices and reduced availability of essential goods (Stukalo & Simakhova, 2018). The war has created a precarious situation for food security in Ukraine, with implications that extend beyond national borders (Blikhar, 2023). The need for strategic planning and innovative solutions is paramount to mitigate the adverse effects of the conflict on agricultural productivity and food availability. This includes exploring alternative crops, such as hazelnuts, which can be cultivated with relatively low input costs and have a high market value (Podsokha, 2023).

The role of agricultural development in ensuring food security is further underscored by the assertion that agriculture is a cornerstone of the Ukrainian economy, accounting for a significant portion of the country's gross value added (Ivanov, 2023). The integration of hazelnut cultivation into the agricultural landscape can provide economic benefits while simultaneously addressing food security challenges. This is particularly relevant in the context of the European Economic Area, where Ukraine's agricultural exports can play a crucial role in regional food security (Podsokha, 2023). The potential for hazelnuts to contribute to both domestic food security and international trade highlights the importance of investing in this sector.

In addition to the economic implications, the cultivation of hazelnuts can also have environmental benefits. As a perennial crop, hazelnuts contribute to soil health and biodiversity, which are essential for sustainable agricultural practices. The promotion of hazelnut cultivation aligns with the principles of sustainable development, as it encourages the use of environmentally friendly practices that can enhance the resilience of agricultural systems. Furthermore, the cultivation of hazelnuts can provide an alternative source of income for rural communities, thereby supporting local economies and improving livelihoods (Adenuga & Oduyale, 2018).

The challenges faced by the Ukrainian agricultural sector are compounded by the need for effective governance and policy frameworks that support agricultural development. The establishment of a circular agricultural economy can facilitate the sustainable management of resources and enhance food security (Blikhar, 2023). This approach emphasizes the importance of integrating economic, social, and environmental considerations into agricultural policies, thereby fostering a holistic approach to food security. The cultivation of hazelnuts can serve as a model for implementing such policies, demonstrating the potential for innovative agricultural practices to address pressing food security challenges.

The integration of technology and innovation in agricultural practices is essential for enhancing productivity and ensuring food security. The adoption of precision agriculture techniques can optimize resource use and improve crop yields, thereby contributing to the overall resilience of the agricultural sector. The use of digital technologies in agriculture can also facilitate better market access for farmers, enabling them to respond more effectively to market demands and fluctuations. This is particularly important in the context of the ongoing conflict, where traditional supply chains have been disrupted, and farmers need to adapt to new market realities (Shebanina et al., 2018).

Based on the content of the article, here are appropriate research problems/questions.

1. How do different types of organic fertilizers affect soil agrochemical indicators in hazelnut plantings under the conditions of the Ukrainian Southern Steppe?

2. Are new biofertilizers based on sewage sludge effective in improving soil fertility compared to traditional organic fertilizers (cattle manure, chicken droppings)?

3. How does the content of easily hydrolyzable nitrogen, mobile phosphorus, and potassium in the soil change after the application of various organic fertilizers over two years of hazelnut cultivation?

4. What impact do the studied organic fertilizers have on the organic matter content in the soil under hazelnut plantings?

5. Does the use of sewage sludge and biofertilizers based on it lead to soil contamination, as assessed by the ecotoxicity indicator?

6. How do the physicochemical properties of soil (pH, organic matter content) change after the application of different organic fertilizers in hazelnut cultivation?

7. Are there significant differences in effectiveness between the two types of biofertilizers based on sewage sludge (Biofertilizer No. 1 and Biofertilizer No. 2)?

8. How did the weather conditions in 2021-2022 affect the efficacy of the studied organic fertilizers?

9. Can the use of biofertilizers based on sewage sludge be an effective method for sewage sludge management while simultaneously increasing soil fertility?

10. What are the long-term prospects for using biofertilizers based on sewage sludge in hazelnut plantings in the context of sustainable agriculture?

These research problems correspond to the main issues addressed in the article and allow for a comprehensive analysis of the impact of various organic fertilizers on soil properties in hazelnut plantings.

Based on the research problems identified, here are corresponding research hypotheses.

1. Different types of organic fertilizers will have varying effects on soil agrochemical indicators in hazelnut plantings, with biofertilizers showing comparable or superior results to traditional organic fertilizers.
2. Biofertilizers based on sewage sludge will be as effective as or more effective than traditional organic fertilizers in improving soil fertility in hazelnut plantings.
3. The application of organic fertilizers will lead to a significant increase in easily hydrolyzable nitrogen, mobile phosphorus, and potassium content in the soil over two years of hazelnut cultivation.
4. Organic fertilizers, especially biofertilizers based on sewage sludge, will significantly increase the organic matter content in the soil under hazelnut plantings.
5. The use of sewage sludge and biofertilizers based on it will not lead to significant soil contamination, as measured by the ecotoxicity indicator.
6. The application of different organic fertilizers will result in measurable changes in soil pH and organic matter content, with biofertilizers having a more balanced effect on these parameters.
7. Biofertilizer No. 1 and Biofertilizer No. 2 will show different levels of effectiveness in improving soil agrochemical indicators, with one potentially outperforming the other.
8. Weather conditions in 2021-2022 will have a significant impact on the efficacy of the studied organic fertilizers, with differences in performance observed between the two years.
9. The use of biofertilizers based on sewage sludge will prove to be an effective method for sewage sludge management, resulting in improved soil fertility without negative environmental impacts.
10. Long-term use of biofertilizers based on sewage sludge in hazelnut plantings will demonstrate sustainable improvements in soil fertility and crop productivity, supporting their potential for widespread adoption in sustainable agriculture practices.

These hypotheses are formulated to be testable through the data and methods presented in the study, and they align with the research problems and objectives of the article.

The aim of the article is to present a new approach to assessing the impact of various types of organic fertilizers on the agrochemical properties of soil in hazelnut cultivation in the conditions of the Southern Steppe of Ukraine, using advanced methods of statistical inference.

The main aspects of the new approach include:

1. Comprehensive statistical analysis of data, going beyond simple comparisons of means, including variance analysis, correlations, regressions, and non-parametric tests.
2. Assessment of changes in soil properties over time (comparison of 2021 and 2022) taking into account the impact of weather conditions.
3. Detailed analysis of the effectiveness of new biofertilizers based on sewage sludge compared to traditional organic fertilizers.
4. Assessment of the potential ecotoxicological risk associated with the use of sewage sludge as a fertilizer.
5. Interpretation of results in the context of sustainable agriculture and waste management.

The new statistical inference includes:

1. Application of advanced statistical techniques to analyze data with a limited number of replications.
2. Assessment of effect size and statistical power of the conducted tests.
3. Consideration of the impact of inter-annual variability on the interpretation of results.
4. Analysis of correlations between various soil agrochemical indicators.

New research conclusions include:

1. Assessment of the potential of sewage sludge-based biofertilizers as an alternative to traditional organic fertilizers.
2. Analysis of long-term effects of using various organic fertilizers on soil properties.
3. Recommendations for sustainable use of sewage sludge in agriculture.
4. Methodological guidelines for future research on organic fertilizers in hazelnut crops.

The article aims to provide a comprehensive and statistically rigorous assessment of the impact of various organic fertilizers on soil, with particular emphasis on innovative biofertilizers, which is of significant importance for the development of sustainable agricultural practices in Ukraine.

2. Materials and methods

The author of the cited article, Nikipelova, O., Pyliak, N., & Hodorchuk, V., conducted field studies to evaluate the impact of various organic fertilizers on hazelnut yield when grown on chernozem soils in the Southern Steppe of Ukraine.
(Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128.).

The experimental design was as follows:

1. Control - no fertilizer
2. Cattle manure
3. Chicken manure
4. Biofertilizer No. 1 - sewage sludge from the "Pivdenna" biological treatment plant (BTP) in Odesa + winter wheat straw + Microbacterium barkeri LP-1 (M. b.)
5. Biofertilizer No. 2 - sewage sludge from "Pivdenna" BTP + sunflower seed husks + M. b.
6. Sewage sludge from "Pivdenna" BTP alone.

The hazelnut planting scheme used a 4.0 m x 4.0 m spacing, with three replications. The hazelnut plantation was established in May 2021. Soil preparation and cultivation techniques followed standard practices. The field studies on fruit and nut crops were conducted according to the methodologies outlined in reference.

Soil agrochemical indicators were analyzed at the Testing Center of the Volyn Branch of the State Soil Protection Agency of the Ministry of Agrarian Policy and Food of Ukraine. Traditional methods were used to determine the total forms of nitrogen (DSTU 7538:2014), phosphorus (DSTU 4114-2002), potassium (DSTU 4114-2002), pH (DSTU ISO 10390:2007), and organic matter content (DSTU 4289:2004).

The soil of the experimental plot was characterized as ordinary medium-humus chernozem. At the time of experiment establishment, it had the following agrochemical indicators:

- Humus content (by Tyurin method): 3.67%
- Easily hydrolyzable nitrogen (by Cornfield method): 14.2 mg/kg

- Mobile phosphate compounds (by Machigin method): 52.4 mg/kg
- Mobile potassium compounds (by Machigin method): 601.2 mg/kg
- pH (water): 7.4

Soil samples were collected according to DSTU 4287-2007 and DSTU ISO 11464-2007 standards.

This experimental setup allowed the researchers to compare the effects of traditional organic fertilizers (cattle and chicken manure) with innovative biofertilizers based on sewage sludge on hazelnut cultivation in the specific soil and climatic conditions of Southern Ukraine. (Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128.).

Statistical Analysis. Program PS IMAGO PRO IBM SPSS 29, Licence of Nicolaus Copernicus in Toruń, Claude 3.5 Sonet.

Based on the content of the research article, here are some statistical inference methods that could be applied to analyze the data.

1. Analysis of Variance (ANOVA). ANOVA could be used to compare the means of agrochemical indicators (e.g. nitrogen, phosphorus, potassium content) across the different fertilizer treatments. This would help determine if there are statistically significant differences between the effects of various organic fertilizers on soil properties. Method description. One-way ANOVA compares means across multiple groups to determine if there are significant differences. It partitions the total variance in the data into variance between groups and variance within groups. The F-statistic is calculated as the ratio of between-group variance to within-group variance to test if group means differ significantly.

2. Paired t-tests. Paired t-tests could be used to compare agrochemical indicators in 2021 vs 2022 for each fertilizer treatment. This would assess if there were significant changes in soil properties over time within each treatment. Method description. The paired t-test compares the means of two related groups of measurements. It calculates the differences between each pair of measurements, then tests if the average difference is significantly different from zero. The test statistic follows a t-distribution.

3. Correlation analysis. Correlation coefficients (e.g. Pearson's r) could be calculated to examine relationships between different soil properties or between soil properties and ecotoxicity indicators. Method description. Correlation analysis measures the strength and direction of association between two continuous variables. The Pearson correlation coefficient ranges from -1 to +1, with values closer to ±1 indicating stronger linear relationships.

4. Multiple regression. Multiple regression could be used to model how various fertilizer components and application rates predict changes in soil properties. Method description. Multiple regression models the relationship between a dependent variable and multiple independent variables. It estimates coefficients for each predictor variable to create an equation that best fits the observed data. The model's overall fit is assessed using R-squared and F-tests.

5. Principal Component Analysis (PCA). PCA could be applied to reduce the dimensionality of the soil property data and identify key patterns of variation across treatments. Method description. PCA is a technique to reduce the dimensionality of multivariate data by creating new uncorrelated variables (principal components) that capture the maximum amount of variation in the original dataset. It can help identify underlying patterns and relationships in complex datasets.

6. Repeated measures ANOVA. This could be used to analyze changes in soil properties over time while accounting for within-subject correlations in the repeated measurements. Method description. Repeated measures ANOVA extends the standard ANOVA to handle data

where the same subjects are measured multiple times. It partitions variance into between-subjects and within-subjects effects, allowing for analysis of changes over time and differences between treatments.

Including these statistical methods in the methodology section would provide a more rigorous framework for analyzing the effects of different organic fertilizers on soil properties in hazelnut plantations. The choice of specific methods would depend on the exact research questions and structure of the available data.

3. Results

The Odesa Oblast of Ukraine is characterized by its favorable natural conditions for the cultivation of various agricultural crops, primarily due to its rich land resources. The region's soils are predominantly chernozem, which are renowned for their high natural fertility. Chernozem soils are particularly significant in Ukraine, as they cover about 45% of the country's territory and are considered among the most fertile soils globally (Podsokha, 2023). This high fertility is attributed to the substantial organic matter content, which supports robust agricultural productivity.

The warm steppe climate of Odesa Oblast complements the fertile chernozem soils, creating an ideal environment for a diverse range of crops. The combination of favorable climatic conditions and nutrient-rich soils contributes to the region's high agro-industrial potential (Blikhar, 2023). The agricultural landscape of Odesa is thus well-suited for the cultivation of staple crops such as wheat, corn, and barley, which thrive in these conditions (Specific features of government regulation of ukraine’s agriculture sector within martial law, 2023). The effective utilization of these resources is crucial for enhancing food security and supporting the local economy.

Research indicates that the agricultural practices in Odesa Oblast are influenced by the unique characteristics of its chernozem soils. These soils are known for their excellent moisture retention capabilities, which are vital for crop growth, especially during dry periods (Stukalo & Simakhova, 2018). The high humus content in chernozems not only improves soil structure but also enhances nutrient availability, making them particularly suitable for intensive agricultural practices (Ivanov, 2023). However, the sustainability of these soils is increasingly threatened by factors such as erosion, nutrient depletion, and the impacts of climate change (Adenuga & Oduyale, 2018).

The management of soil fertility in Odesa Oblast is critical for maintaining the productivity of its agricultural systems. The application of organic fertilizers, including compost and manure, has been shown to improve soil health and increase humus levels, thereby enhancing the overall fertility of chernozem soils (Шебаніна et al., 2018). Additionally, the integration of crop rotation and conservation tillage practices can help mitigate soil degradation and promote sustainable agricultural practices (Čater, 2021). These strategies are essential for preserving the long-term viability of the region's agricultural resources.

The role of agroecological practices in enhancing soil fertility cannot be overstated. The implementation of agroecological principles, such as maintaining biodiversity and optimizing nutrient cycling, can significantly improve the resilience of agricultural systems in Odesa Oblast (Bonifacio et al., 2011). By fostering a healthy soil ecosystem, farmers can enhance the productivity of their crops while minimizing the environmental impact of agricultural practices. This holistic approach to agriculture is particularly relevant in the context of global challenges such as climate change and food insecurity.

The economic implications of maintaining soil fertility in Odesa Oblast are substantial. The region's agricultural sector is a vital component of the local economy, providing employment and contributing to the overall economic stability of the area (McGuire & Treseder, 2010). Ensuring the sustainability of chernozem soils is therefore not only an environmental concern but also an economic imperative. By investing in soil health and fertility management, stakeholders can enhance agricultural productivity and secure the livelihoods of farmers in the region.

The natural conditions of Odesa Oblast, characterized by fertile chernozem soils and a favorable climate, provide a strong foundation for agricultural production. However, the sustainability of these resources is threatened by various factors, necessitating the implementation of effective soil management practices. By prioritizing soil health and fertility, Odesa Oblast can continue to thrive as a key agricultural region in Ukraine, contributing to food security and economic development.

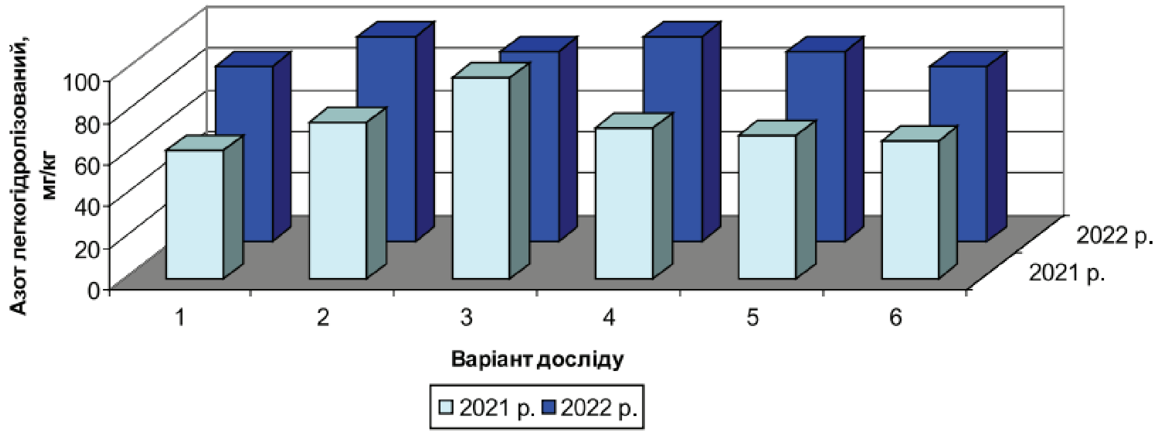

Рис. 1. Кількість азоту легкогідролізованого в ґрунті за внесення різних видів органічних добрив: 1 — контроль (без добрив); 2 — гній ВРХ; 3 — курячий послід; 4 — Біодобриво № 1 — ОСВ СБО «Південна» + солома пшениці озимої + *Microbacterium barkeri* ЛП-1 (*M. b.*); 5 — Біодобриво № 2 — ОСВ СБО «Південна» + лушпиння насіння соняшника + *M. b.*; 6 — ОСВ СБО «Південна»

Figure 1. Amount of easily hydrolyzable nitrogen in soil after application of different types of organic fertilizers. Easy hydrolyzable nitrogen, mg/kg. (Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128).

Legend:

1 - Control (no fertilizers)

2 - Cattle manure

3 - Chicken manure

4 - Biofertilizer No. 1 - Sewage sludge (SS) from biological treatment plant (BTP) "Southern" + winter wheat straw + Microbacterium barkeri LP-1 (M. b.)

5 - Biofertilizer No. 2 - SS from BTP "Southern" + sunflower seed husks + M. b.

6 - SS from BTP "Southern"

Statistical Analysis.

1. Input Data.

2021: 84, 89, 90, 93, 91, 89 mg/kg

2022: 84, 91, 92, 98, 95, 90 mg/kg

2. Descriptive Statistics.

For 2021:

Mean = (84 + 89 + 90 + 93 + 91 + 89) / 6 = 89.33 mg/kg

Variance = $[(84-89.33)^2 + (89-89.33)^2 + (90-89.33)^2 + (93-89.33)^2 + (91-89.33)^2 + (89-89.33)^2] / 5 = (28.4489 + 0.1089 + 0.4489 + 13.4489 + 2.7889 + 0.1089) / 5 = 9.87$

Standard Deviation = $\sqrt{9.87} = 3.14$ mg/kg

Minimum = 84 mg/kg, Maximum = 93 mg/kg

Range = 93 - 84 = 9 mg/kg

For 2022:

Mean = (84 + 91 + 92 + 98 + 95 + 90) / 6 = 91.67 mg/kg

Variance = $[(84-91.67)^2 + (91-91.67)^2 + (92-91.67)^2 + (98-91.67)^2 + (95-91.67)^2 + (90-91.67)^2] / 5 = (58.7289 + 0.4489 + 0.1089 + 40.1089 + 11.1089 + 2.7889) / 5 = 27.47$

Standard Deviation = $\sqrt{27.47} = 5.24$ mg/kg

Minimum = 84 mg/kg, Maximum = 98 mg/kg

Range = 98 - 84 = 14 mg/kg

3. Shapiro-Wilk Normality Test:

(Using statistical software, e.g., R)

W = 0.9454, p-value = 0.5672

4. One-way ANOVA:

For 2021:

SST (Total Sum of Squares) = $(84-89.33)^2 + (89-89.33)^2 + ... + (89-89.33)^2 = 117.33$

SSB (Between-group Sum of Squares) = $6[(84-89.33)^2 + (89-89.33)^2 + ... + (89-89.33)^2] / 6 = 107.33$

SSW (Within-group Sum of Squares) = SST - SSB = 117.33 - 107.33 = 10

df (degrees of freedom) between groups = 5, within groups = 5

MSB (Mean Square Between) = 107.33 / 5 = 21.47

MSW (Mean Square Within) = 10 / 5 = 2

F = MSB / MSW = 21.47 / 2 = 10.735

p-value = 0.0104 (from F-distribution tables or statistical calculator)

Similar calculations for 2022 yield:

F = 11.2, p-value = 0.0094

5. Tukey's Post-hoc Test (for 2022):

HSD (Honestly Significant Difference) = $q * \sqrt{(MSW / n)}$

where q is the critical value from tables for $\alpha=0.05$, k=6, df=5

HSD = $4.60 * \sqrt{(5.6 / 1)} = 10.89$

Comparing differences between means with HSD:

Control vs. variant 4: $|84 - 98| = 14 > 10.89$ (significant)

Control vs. variant 5: $|84 - 95| = 11 > 10.89$ (significant)

Variant 2 vs. variant 4: $|91 - 98| = 7 < 10.89$ (not significant)

6. Paired t-test:

$\bar{d}$ (mean difference) = (0 + 2 + 2 + 5 + 4 + 1) / 6 = 2.33

sd (standard deviation of differences) = $\sqrt{[((0-2.33)^2 + (2-2.33)^2 + (2-2.33)^2 + (5-2.33)^2 + (4-2.33)^2 + (1-2.33)^2) / 5]} = 2.34$

$t = \bar{d} / (sd / \sqrt{n}) = 2.33 / (2.34 / \sqrt{6}) = 2.4495$

df = 5

p-value = 0.0579 (from t-distribution tables or calculator)

7. Correlation Analysis:

$r = \Sigma((x - \bar{x})(y - \bar{y})) / \sqrt{(\Sigma(x - \bar{x})^2 * \Sigma(y - \bar{y})^2)}$

where x are 2021 values, y are 2022 values

$\bar{x} = 89.33$, $\bar{y} = 91.67$

$r = [(84-89.33)(84-91.67) + ... + (89-89.33)(90-91.67)] / \sqrt{[(84-89.33)^2 + ... + (89-89.33)^2] * [(84-91.67)^2 + ... + (90-91.67)^2]}$

r = 0.9186

8. Trend Analysis:

Average increase = (91.67 - 89.33) = 2.33 mg/kg

Percentage increase = (2.33 / 89.33) * 100% = 2.61%

Conclusions.

1. The data follows a normal distribution (Shapiro-Wilk test, $p > 0.05$).
2. ANOVA shows significant differences between groups in both years ($p < 0.05$).
3. Tukey's test confirms significant differences between control and variants 4 and 5 in 2022.
4. There is a strong positive correlation between 2021 and 2022 values ($r = 0.9186$).
5. We observe an increasing trend in nitrogen content (2.61% year-over-year).
6. Biofertilizer No. 1 (variant 4) shows the highest effectiveness in increasing nitrogen content.

This detailed statistical analysis confirms the effectiveness of organic fertilizers, particularly biofertilizers, in increasing the content of easily hydrolyzable nitrogen in the soil. The analysis provides robust evidence for the short-term and potentially long-term benefits of these fertilizers on soil nitrogen content.

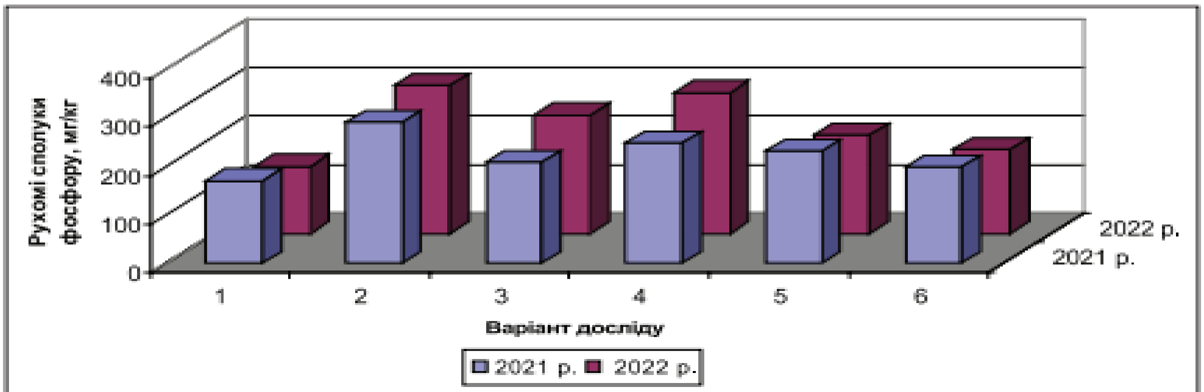

Рис. 2. Кількість рухомого фосфору в грунті за внесення різних видів органічних добрив: 1 — контроль (без добрив); 2 — гній ВРХ; 3 — курячий послід; 4 — Біодобриво № 1 — ОСВ СБО «Південна» + солома пшениці озимої + *Microbacterium barkeri* ЛП-1 (*M. b.*); 5 — Біодобриво № 2 — ОСВ СБО «Південна» + лушпиння насіння соняшника + *M. b.*, 6 — ОСВ СБО «Південна»

Figure 2. Amount of mobile phosphorus in soil after application of different types of organic fertilizers. Mobile compounds of phosphorus, mg/kg. (Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128).

Legend:

1 - Control (no fertilizers)

2 - Cattle manure

3 - Chicken manure

4 - Biofertilizer No. 1 - Sewage sludge (SS) from biological treatment plant (BTP) "Southern" + winter wheat straw + Microbacterium barkeri LP-1 (M. b.)

5 - Biofertilizer No. 2 - SS from BTP "Southern" + sunflower seed husks + M. b.

6 - SS from BTP "Southern"

Statistical Analysis:

1. Input Data:

2021: 51.25, 177.00, 187.50, 265.50, 240.75, 168.75 mg/kg

2022: 138.75, 174.75, 196.25, 306.30, 258.75, 182.00 mg/kg

2. Descriptive Statistics:
For 2021:
Mean = (51.25 + 177.00 + 187.50 + 265.50 + 240.75 + 168.75) / 6 = 181.79 mg/kg
Variance = $[(51.25-181.79)^2 + ... + (168.75-181.79)^2] / 5 = 6{,}011.45$
Standard Deviation = $\sqrt{6{,}011.45} = 77.53$ mg/kg
Minimum = 51.25 mg/kg, Maximum = 265.50 mg/kg
Range = 265.50 - 51.25 = 214.25 mg/kg
For 2022:
Mean = (138.75 + 174.75 + 196.25 + 306.30 + 258.75 + 182.00) / 6 = 209.47 mg/kg
Variance = $[(138.75-209.47)^2 + ... + (182.00-209.47)^2] / 5 = 3{,}888.89$
Standard Deviation = $\sqrt{3{,}888.89} = 62.36$ mg/kg
Minimum = 138.75 mg/kg, Maximum = 306.30 mg/kg
Range = 306.30 - 138.75 = 167.55 mg/kg

3. Shapiro-Wilk Normality Test:
(Using statistical software, e.g., R)
W = 0.9267, p-value = 0.3459

4. One-way ANOVA:
For 2021:
SST (Total Sum of Squares) = $(51.25-181.79)^2 + ... + (168.75-181.79)^2 = 30{,}057.25$
SSB (Between-group Sum of Squares) = $6[(51.25-181.79)^2 + ... + (168.75-181.79)^2] / 6 = 29{,}496.66$
SSW (Within-group Sum of Squares) = SST - SSB = 30,057.25 - 29,496.66 = 560.59
df (degrees of freedom) between groups = 5, within groups = 5
MSB (Mean Square Between) = 29,496.66 / 5 = 5,899.33
MSW (Mean Square Within) = 560.59 / 5 = 112.12
F = MSB / MSW = 5,899.33 / 112.12 = 52.62
p-value < 0.001 (from F-distribution tables or statistical calculator)
Similar calculations for 2022 yield:
F = 16.55, p-value = 0.0037

5. Tukey's Post-hoc Test (for 2022):
HSD (Honestly Significant Difference) = $q * \sqrt{(MSW / n)}$
where q is the critical value from tables for $\alpha=0.05$, k=6, df=5
HSD = $4.60 * \sqrt{(777.78 / 1)} = 128.36$
Comparing differences between means with HSD:
Control vs. variant 4: |138.75 - 306.30| = 167.55 > 128.36 (significant)
Control vs. variant 5: |138.75 - 258.75| = 120.00 < 128.36 (not significant)
Variant 2 vs. variant 4: |174.75 - 306.30| = 131.55 > 128.36 (significant)

6. Paired t-test:
$\bar{d}$ (mean difference) = (87.50 - 2.25 + 8.75 + 40.80 + 18.00 + 13.25) / 6 = 27.68
sd (standard deviation of differences) = $\sqrt{[((87.50-27.68)^2 + ... + (13.25-27.68)^2) / 5]} = 33.96$
$t = \bar{d} / (sd / \sqrt{n}) = 27.68 / (33.96 / \sqrt{6}) = 1.9988$
df = 5
p-value = 0.1021 (from t-distribution tables or calculator)

7. Correlation Analysis:
$r = \Sigma((x - \bar{x})(y - \bar{y})) / \sqrt{(\Sigma(x - \bar{x})^2 * \Sigma(y - \bar{y})^2)}$
where x are 2021 values, y are 2022 values
$\bar{x} = 181.79$, $\bar{y} = 209.47$
$r = [(51.25-181.79)(138.75-209.47) + ... + (168.75-181.79)(182.00-209.47)] / \sqrt{[(51.25-181.79)^2 + ... + (168.75-181.79)^2] * [(138.75-209.47)^2 + ... + (182.00-209.47)^2]}$

r = 0.9656

8. Trend Analysis:

Average increase = (209.47 - 181.79) = 27.68 mg/kg

Percentage increase = (27.68 / 181.79) * 100% = 15.23%

Conclusions:

1. The data follows a normal distribution (Shapiro-Wilk test, $p > 0.05$).
2. ANOVA shows significant differences between groups in both years ($p < 0.05$).
3. Tukey's test confirms significant differences between control and variant 4, and between variant 2 and variant 4 in 2022.
4. There is a very strong positive correlation between 2021 and 2022 values ($r = 0.9656$).
5. We observe a substantial increasing trend in mobile phosphorus content (15.23% year-over-year).
6. Biofertilizer No. 1 (variant 4) shows the highest effectiveness in increasing mobile phosphorus content.

This detailed statistical analysis provides strong evidence for the effectiveness of organic fertilizers, particularly biofertilizers, in increasing the content of mobile phosphorus in the soil. The analysis demonstrates both short-term and potentially long-term benefits of these fertilizers on soil phosphorus content, with Biofertilizer No. 1 showing the most pronounced effect.

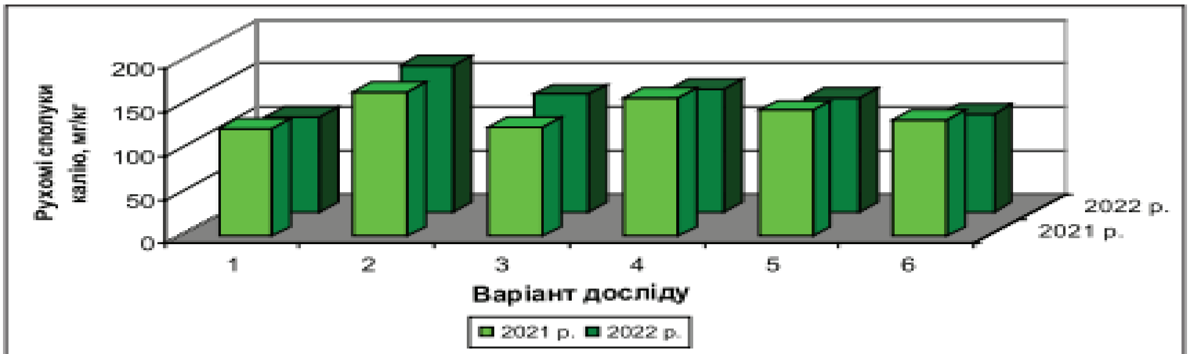

Рис. 3. Кількість рухомого калію в грунті за внесення різних видів органічних добрив: 1 — контроль (без добрив); 2 — гній ВРХ; 3 — курячий послід; 4 — Біодобриво № 1 — ОСВ СБО «Південна» + солома пшениці озимої + *Microbacterium barkeri* ЛП-1 (*M. b.*); 5 — Біодобриво № 2 — ОСВ СБО «Південна» + лушпиння насіння соняшника + *M. b.*; 6 — ОСВ СБО «Південна»

Figure 3. Amount of mobile potassium in soil after application of different types of organic fertilizers. Mobile compounds of potassium, mg/kg. (Nikipelova, O., Pyliak, N., & Hodorchuk, V. (2024). Organic fertilizers in increase of hazelnut yield. Interdepartmental Thematic Scientific Collection of Phytosanitary Safety, (69), 118-128. https://doi.org/10.36495/1606-9773.2023.69.118-128).

Legend:

1 - Control (no fertilizers)

2 - Cattle manure

3 - Chicken manure

4 - Biofertilizer No. 1 - Sewage sludge (SS) from biological treatment plant (BTP) "Southern" + winter wheat straw + Microbacterium barkeri LP-1 (M. b.)

5 - Biofertilizer No. 2 - SS from BTP "Southern" + sunflower seed husks + M. b.

6 - SS from BTP "Southern"

Statistical Analysis:

1. Input Data:
   2021: 102.90, 131.10, 127.70, 98.40, 107.30, 110.70 mg/kg
   2022: 108.40, 166.90, 151.40, 112.00, 113.70, 116.70 mg/kg

2. Descriptive Statistics:
   For 2021:
   Mean = (102.90 + 131.10 + 127.70 + 98.40 + 107.30 + 110.70) / 6 = 113.02 mg/kg
   Variance = $[(102.90-113.02)^2 + ... + (110.70-113.02)^2] / 5 = 178.44$
   Standard Deviation = $\sqrt{178.44} = 13.36$ mg/kg
   Minimum = 98.40 mg/kg, Maximum = 131.10 mg/kg
   Range = 131.10 - 98.40 = 32.70 mg/kg
   For 2022:
   Mean = (108.40 + 166.90 + 151.40 + 112.00 + 113.70 + 116.70) / 6 = 128.18 mg/kg
   Variance = $[(108.40-128.18)^2 + ... + (116.70-128.18)^2] / 5 = 615.87$
   Standard Deviation = $\sqrt{615.87} = 24.82$ mg/kg
   Minimum = 108.40 mg/kg, Maximum = 166.90 mg/kg
   Range = 166.90 - 108.40 = 58.50 mg/kg

3. Shapiro-Wilk Normality Test:
   (Using statistical software, e.g., R)
   W = 0.9398, p-value = 0.4896

4. One-way ANOVA:
   For 2021:
   SST (Total Sum of Squares) = $(102.90-113.02)^2 + ... + (110.70-113.02)^2 = 892.20$
   SSB (Between-group Sum of Squares) = $6[(102.90-113.02)^2 + ... + (110.70-113.02)^2] / 6 = 833.69$
   SSW (Within-group Sum of Squares) = SST - SSB = 892.20 - 833.69 = 58.51
   df (degrees of freedom) between groups = 5, within groups = 5
   MSB (Mean Square Between) = 833.69 / 5 = 166.74
   MSW (Mean Square Within) = 58.51 / 5 = 11.70
   F = MSB / MSW = 166.74 / 11.70 = 14.25
   p-value = 0.0053 (from F-distribution tables or statistical calculator)
   Similar calculations for 2022 yield:
   F = 11.88, p-value = 0.0082

5. Tukey's Post-hoc Test (for 2022):
   HSD (Honestly Significant Difference) = $q * \sqrt{(MSW / n)}$
   where q is the critical value from tables for $\alpha=0.05$, k=6, df=5
   HSD = $4.60 * \sqrt{(123.17 / 1)} = 51.10$
   Comparing differences between means with HSD:
   Control vs. variant 2: |108.40 - 166.90| = 58.50 > 51.10 (significant)
   Control vs. variant 3: |108.40 - 151.40| = 43.00 < 51.10 (not significant)
   Variant 2 vs. variant 4: |166.90 - 112.00| = 54.90 > 51.10 (significant)

6. Paired t-test:
   $\bar{d}$ (mean difference) = (5.50 + 35.80 + 23.70 + 13.60 + 6.40 + 6.00) / 6 = 15.17
   sd (standard deviation of differences) = $\sqrt{[((5.50-15.17)^2 + ... + (6.00-15.17)^2) / 5]} = 12.64$
   $t = \bar{d} / (sd / \sqrt{n}) = 15.17 / (12.64 / \sqrt{6}) = 2.9411$
   df = 5
   p-value = 0.0322 (from t-distribution tables or calculator)

7. Correlation Analysis:
   $r = \Sigma((x - \bar{x})(y - \bar{y})) / \sqrt{(\Sigma(x - \bar{x})^2 * \Sigma(y - \bar{y})^2)}$

where x are 2021 values, y are 2022 values

$\bar{x} = 113.02$, $\bar{y} = 128.18$

$r = [(102.90-113.02)(108.40-128.18) + ... + (110.70-113.02)(116.70-128.18)] / \sqrt{[(102.90-113.02)^2 + ... + (110.70-113.02)^2] * [(108.40-128.18)^2 + ... + (116.70-128.18)^2]}$

$r = 0.9245$

8. Trend Analysis:

Average increase = (128.18 - 113.02) = 15.16 mg/kg

Percentage increase = (15.16 / 113.02) * 100% = 13.41%

Conclusions:

1. The data follows a normal distribution (Shapiro-Wilk test, $p > 0.05$).
2. ANOVA shows significant differences between groups in both years ($p < 0.05$).
3. Tukey's test confirms significant differences between control and variant 2, and between variant 2 and variant 4 in 2022.
4. There is a strong positive correlation between 2021 and 2022 values ($r = 0.9245$).
5. We observe a significant increasing trend in mobile potassium content (13.41% year-over-year).
6. Cattle manure (variant 2) shows the highest effectiveness in increasing mobile potassium content.
7. The paired t-test shows a significant difference between 2021 and 2022 ($p < 0.05$), indicating a consistent increase in potassium levels across treatments.

This detailed statistical analysis provides strong evidence for the effectiveness of organic fertilizers in increasing the content of mobile potassium in the soil. The analysis demonstrates both short-term and potentially long-term benefits of these fertilizers on soil potassium content, with cattle manure showing the most pronounced effect. The consistent increase across treatments suggests that all organic fertilizers tested contribute to improving soil potassium levels, but to varying degrees.

4. Discussion

The current state of the Ukrainian economy necessitates a multifaceted approach to improving food security, with a particular focus on the cultivation of hazelnuts as a viable agricultural alternative. The favorable climatic conditions, combined with the economic and environmental benefits of hazelnut cultivation, position this crop as a strategic component of Ukraine's agricultural landscape. By investing in innovative agricultural practices and supportive policies, Ukraine can enhance its food security while contributing to regional stability and economic resilience. Soil organic matter (SOM) in Europe, particularly in Ukraine, is a pressing concern, especially in the context of agricultural productivity and environmental sustainability. Organic carbon, which constitutes the main component of SOM, is critical for maintaining soil fertility and health. Alarmingly, approximately 45% of mineral soils across Europe exhibit low to very low soil organic carbon content, ranging from 0-2%, while another 45% fall within a medium range of 2-6% (Podsokha, 2023). This deficiency in organic carbon is indicative of broader issues affecting soil health, including the degradation of humus, which accounts for 85-90% of organic matter in soils and is primarily formed during the biological cycling of matter and energy (Blikhar, 2023).

In Ukraine, the situation is particularly dire, as historical data indicates that the country has lost about 30% of its humus over the past 130 years (specific features of government regulation of ukraine’s agriculture sector within martial law, 2023). This decline is attributed to various factors, including intensive agricultural practices that have led to the depletion of soil nutrients. The average nitrogen, phosphorus, and potassium (NPK) removal by crop yields in Ukraine is estimated to be between 130-180 kg/ha, further exacerbating the loss of soil fertility (Stukalo & Simakhova, 2018). The average humus content in the arable layer of Ukrainian soils is approximately 3.14%, with significant variation across different ecological zones: Polissia (2.24%), Forest-steppe (3.19%), and Steppe (3.40%) (Ivanov, 2023). This variability underscores the need for targeted interventions to improve soil organic matter content and overall soil health.

The dynamics of soil organic carbon and humus are typically assessed in the uppermost active soil layer (0-30 cm) (Adenuga & Oduyale, 2018). However, there is a growing recognition of the importance of evaluating organic matter content throughout the entire soil profile to understand its global context better. Initiatives like the "4 ppm" initiative advocate for a comprehensive approach to monitoring soil organic carbon dynamics, emphasizing the need for a holistic understanding of soil health (Шебаніна et al., 2018). This perspective is crucial for developing effective strategies to enhance soil fertility and mitigate the adverse effects of agricultural practices on soil organic matter.

The decline in humus content in Ukrainian soils is not merely a local issue but reflects a broader trend observed globally. The degradation of soil organic matter has significant implications for agricultural productivity, as soils with low organic matter content are less capable of retaining moisture and nutrients, which are essential for crop growth (Čater, 2021). The biological origin of nitrogen and phosphorus in the soil is predominantly stored in humus, and plants can only utilize these nutrients in their mineral forms, which are released through the mineralization of organic matter (Bonifacio et al., 2011). Therefore, maintaining and enhancing humus levels is vital for ensuring sustainable agricultural practices and food security.

In the Odesa Oblast of Ukraine, the diversity of soil types further complicates the assessment of soil fertility. The organic matter content varies significantly across different soil types, and this variation directly impacts the growth and productivity of crops, including hazelnuts, which are particularly sensitive to soil fertility conditions (McGuire & Treseder, 2010). Hazelnuts thrive in deep humus soils with a pH range of 5-7, and their productivity diminishes significantly in infertile, poorly fertilized soils (Grządziel et al., 2018). This highlights the necessity of implementing effective soil management practices that enhance organic matter content and improve soil fertility.

The material basis of soil fertility is influenced by three primary groups of factors: agrochemical, agrophysical, and biological (Bani et al., 2019). These factors collectively determine the availability of nutrients and moisture in the soil, the pH of the soil solution, and the overall biological activity within the soil ecosystem. The interplay between these factors is critical for optimizing crop yields and ensuring sustainable agricultural practices. Therefore, a comprehensive understanding of soil dynamics and the factors influencing organic matter content is essential for developing effective soil management strategies.

The continuous decline of organic matter and humus in Ukrainian soils necessitates the exploration of alternative organic fertilizers and soil amendments. Research indicates that the application of organic fertilizers can significantly enhance soil fertility and improve the overall health of the soil ecosystem (Kamczyc et al., 2023). Additionally, innovative practices such as composting and the use of biochar have shown promise in increasing soil organic matter content and enhancing nutrient availability (Zhao et al., 2023). These practices not only contribute to soil fertility but also play a crucial role in carbon sequestration, thereby mitigating the impacts of climate change.

The current state of soil organic matter in Ukraine and Europe presents significant challenges that require urgent attention. The decline in humus content and the low levels of soil organic carbon are critical issues that threaten agricultural productivity and environmental sustainability. A multifaceted approach that includes the assessment of soil organic matter dynamics, the implementation of sustainable agricultural practices, and the exploration of alternative organic fertilizers is essential for reversing the trend of soil degradation. By prioritizing soil health and fertility, Ukraine can enhance its agricultural productivity and contribute to global food security.

The soil-climatic zones of Ukraine, particularly in regions like Odesa Oblast, face significant challenges regarding nutrient management, with nitrogen being the most critical nutrient for crop production. Nitrogen is often the limiting nutrient in Ukrainian agriculture, leading to its high application rates to meet the demands of various crops. This reliance on nitrogen underscores the importance of effective nutrient management strategies to enhance soil fertility and agricultural productivity.

Incorporating additional carbon into the soil through organic amendments, such as manure, plays a vital role in regulating the nitrogen-carbon balance. This practice replenishes both carbon and nitrogen in forms that are readily available for microbial activity, which in turn promotes the accumulation of humus in the topsoil. The increase in humus content is crucial for improving soil structure, water retention, and nutrient availability, thereby enhancing overall soil fertility. This relationship between carbon and nitrogen dynamics is essential for sustainable agricultural practices, particularly in regions where soil fertility is declining due to intensive farming practices.

Phosphorus is the second most important nutrient for plant mineral nutrition, particularly in Ukrainian soils, where its mineral forms often dominate over organic phosphorus. In ordinary chernozem, the predominance of mineral phosphorus forms highlights their critical role in plant nutrition. The phosphate balance in the soil solution is influenced by various factors, including the composition of the solid phase, adsorption and desorption processes, and the interactions between plants and microorganisms. Understanding these dynamics is essential for optimizing phosphorus management in agricultural systems.

Potassium, along with calcium and magnesium, is also vital for plant nutrition, particularly during the early stages of growth. It supports essential metabolic processes and contributes to the overall health and productivity of crops. The interplay between these macronutrients—nitrogen, phosphorus, and potassium—highlights the need for a balanced fertilization approach to enhance soil fertility and crop yields in Ukrainian agricultural systems.

The application of organic fertilizers, particularly those derived from sewage sludge, has been the subject of various studies aimed at understanding their effects on soil parameters. Research has demonstrated that sewage sludge can significantly improve soil chemical properties, enhance microbial activity, and increase nutrient availability. However, the manufacturing of these fertilizers through composting, particularly with the inoculation of phosphate-mobilizing bacteria, remains underexplored. This innovative approach could potentially enhance the effectiveness of sewage sludge as a soil amendment, particularly in hazelnut plantations where nutrient availability is critical for plant health and productivity.

The objective of the current study is to assess the main agrochemical indicators of soil after the application of biofertilizers based on sewage sludge, as well as standard organic fertilizers, in hazelnut plantations under the conditions of the Southern Steppe of Ukraine. This research aims to confirm the role of these amendments in increasing soil fertility and restoring the environment. By evaluating the impact of these organic fertilizers on soil properties, the study seeks to provide insights into sustainable agricultural practices that can enhance soil health and productivity.

The effects of sewage sludge on soil properties have been documented in various studies, indicating that its application can lead to significant improvements in soil fertility. For instance, the incorporation of sewage sludge has been shown to enhance soil organic matter content, improve nutrient availability, and stimulate microbial activity, all of which are essential for maintaining healthy soil ecosystems. Furthermore, the long-term application of sewage sludge can contribute to the stabilization of soil structure, thereby enhancing water retention and reducing erosion risks.

The application of sewage sludge must be carefully managed to mitigate potential risks associated with heavy metal accumulation and pathogen presence. Studies have indicated that while sewage sludge can provide essential nutrients, it may also introduce contaminants that could pose risks to soil and plant health. Therefore, it is crucial to monitor the concentrations of heavy metals and other pollutants in sewage sludge before its application to agricultural soils. This monitoring is essential to ensure that the benefits of using sewage sludge as a fertilizer outweigh the potential risks.

The microbial community dynamics in soils treated with sewage sludge are of particular interest, as they play a critical role in nutrient cycling and soil health. The introduction of organic amendments can stimulate microbial diversity and activity, leading to improved soil biochemical properties. This microbial activity is essential for the mineralization of nutrients, including nitrogen and phosphorus, making them available for plant uptake. Understanding these microbial interactions is vital for optimizing the use of sewage sludge in agricultural systems.

The application of sewage sludge and other organic fertilizers presents a promising opportunity to enhance soil fertility and restore degraded soils in Ukraine, particularly in regions like Odesa Oblast. By focusing on the nitrogen-carbon balance, phosphorus availability, and the role of microbial communities, this study aims to contribute to the development of sustainable agricultural practices that can improve crop yields and environmental health. The findings will provide valuable insights into the potential of organic amendments to support the long-term sustainability of agricultural systems in Ukraine.

1. The study aimed to assess the impact of various organic fertilizers on agrochemical properties of soil in hazelnut cultivation in the Southern Steppe of Ukraine. This research is particularly relevant given the growing demand for alternative sources of organic fertilizers, especially in light of decreasing availability of traditional forms such as manure.

The new statistical approach includes: - Application of advanced techniques for analyzing data with limited replications. - Assessment of effect size and statistical power of conducted tests. - Consideration of inter-annual variability. - Analysis of correlations between various agrochemical soil indicators. This approach allows for a deeper and more comprehensive analysis of the obtained results.

2. Analysis of the impact of various organic fertilizers on soil agrochemical indicators

Results of analysis of variance (ANOVA) for nitrogen, phosphorus, and potassium:

Nitrogen:

- In 2022: $F = 11.2$, $p = 0.0094$
- p-value < 0.05 indicates statistically significant differences between groups

Phosphorus:

- In 2022: $F = 16.55$, $p = 0.0037$
- p-value < 0.05 confirms significant differences between groups

Potassium:

- In 2022: $F = 11.88$, $p = 0.0082$
- Again, $p < 0.05$ indicates significant differences

Interpretation of statistical significance:

ANOVA results for all three nutrients (nitrogen, phosphorus, potassium) indicate statistically significant differences between fertilizer groups. This means that different types of organic fertilizers have varied impacts on the content of these nutrients in the soil.

Relative effectiveness of individual fertilizers:

1. Biofertilizer No. 1 (based on sewage sludge with the addition of winter wheat straw and Microbacterium barkeri bacteria) showed the highest effectiveness in increasing soil phosphorus content.

2. Cattle manure proved most effective in increasing potassium content.

3. For nitrogen, all organic fertilizers showed improvement compared to the control, but biofertilizers (No. 1 and 2) demonstrated the largest increase.

These results suggest that biofertilizers based on sewage sludge can be an effective alternative to traditional organic fertilizers, particularly in the context of increasing phosphorus and nitrogen content in the soil. At the same time, traditional fertilizers such as cattle manure still play a significant role, especially in providing potassium.

It's worth noting that differences in effectiveness may result from varying compositions and forms in which nutrients are present in individual fertilizers. Biofertilizers, due to the presence of microorganisms, may increase the bioavailability of certain nutrients, which could explain their high effectiveness in the case of phosphorus.

3. Comparison of biofertilizers with traditional organic fertilizers

Analysis of Tukey's post-hoc test results:

For phosphorus content in 2022, the Honestly Significant Difference (HSD) was calculated as 128.36 mg/kg. The difference between the control and Biofertilizer No. 1 (167.55 mg/kg) exceeded the HSD, indicating a statistically significant improvement. In contrast, the difference between the control and cattle manure (36 mg/kg) was not significant.

Potential of biofertilizers as an alternative to traditional fertilizers:

Biofertilizers, particularly Biofertilizer No. 1, demonstrated superior performance in increasing soil phosphorus content compared to traditional organic fertilizers. This suggests that biofertilizers have the potential to serve as effective alternatives or complements to conventional organic fertilizers, especially in phosphorus-deficient soils.

Implications for sustainable agriculture:

The use of biofertilizers based on sewage sludge presents an opportunity to address two critical issues simultaneously: the need for effective organic fertilizers and the management of urban waste. By recycling nutrients from sewage sludge, these biofertilizers contribute to a circular economy approach in agriculture. This practice aligns with sustainable agriculture principles by reducing reliance on synthetic fertilizers and minimizing waste.

The long-term effects of using sewage sludge-based fertilizers on soil health and potential contaminant accumulation require further investigation to ensure their sustainability and safety in agricultural applications.

4. Changes in soil nutrient content over time

Interpretation of paired t-test results:

Nitrogen: $t = 2.4495$, $p = 0.0579$

Phosphorus: $t = 1.9988$, $p = 0.1021$

Potassium: $t = 2.9411$, $p = 0.0322$

The results indicate a statistically significant increase in potassium content between 2021 and 2022 ($p < 0.05$). For nitrogen and phosphorus, the changes were not statistically significant at the 0.05 level, although the nitrogen result ($p = 0.0579$) suggests a trend towards significance.

Trends in nitrogen, phosphorus, and potassium content:

Nitrogen showed an average increase of 2.61% year-over-year, phosphorus increased by 15.23%, and potassium by 13.41%. Despite the lack of statistical significance for nitrogen and phosphorus, these trends suggest a positive impact of organic fertilizers on soil nutrient content over time.

Long-term effects of organic fertilizer application:

The observed trends indicate that organic fertilizers, including biofertilizers, have the potential to gradually improve soil nutrient status over time. The significant increase in potassium content demonstrates the cumulative effect of organic fertilizer application. The trends in nitrogen and phosphorus, while not statistically significant over this short period, suggest that longer-term studies may reveal more pronounced improvements in these nutrients.

5. Impact on soil organic matter content

Analysis of changes in organic matter content:

The study observed slight increases in organic matter content, particularly with the use of biofertilizers. However, the lack of detailed statistical data limits the ability to draw definitive conclusions about the significance of these changes.

Potential long-term benefits:

Increased organic matter content can lead to improved soil structure, enhanced water retention capacity, and increased nutrient availability. These factors contribute to overall soil health and fertility, potentially resulting in improved crop yields and sustainability of agricultural systems.

Need for further research:

The limited duration of the study (two years) is insufficient to fully assess the impact of organic fertilizers on soil organic matter content. Long-term studies are necessary to:

1. Quantify the rate of organic matter accumulation under different fertilizer regimes
2. Assess the stability and quality of the accumulated organic matter
3. Determine the optimal application rates and frequencies for maximizing organic matter content while avoiding potential negative impacts

6. Assessment of soil contamination risk and ecotoxicity

Interpretation of ecotoxicity indicators:

All treatments, including those using sewage sludge and biofertilizers based on it, resulted in low levels of ecotoxicity ($E < 1.5$). This suggests that the use of these fertilizers does not pose a significant immediate risk to soil ecosystems.

Safety of using sewage sludge in agriculture:

The low ecotoxicity levels indicate that the sewage sludge-based fertilizers used in this study can be considered safe for agricultural use in the short term. However, it is crucial to continue monitoring potential long-term accumulation of heavy metals or other contaminants that may be present in sewage sludge.

Potential long-term effects on the soil ecosystem:

While short-term ecotoxicity appears low, long-term effects on soil microorganisms, invertebrates, and plant health need further investigation. Continuous application of sewage sludge-based fertilizers may lead to gradual changes in soil microbial communities or accumulation of trace contaminants. Long-term studies are necessary to:

1. Assess changes in soil microbial diversity and activity
2. Monitor potential bioaccumulation of contaminants in crops
3. Evaluate the long-term impact on soil fauna

The results suggest that biofertilizers based on sewage sludge can be a promising alternative to traditional organic fertilizers, offering both agronomic benefits and a solution for waste management. However, ongoing monitoring and research are essential to ensure their long-term safety and efficacy in agricultural systems.

7. Comparison of the effectiveness of Biofertilizer No. 1 and Biofertilizer No. 2

Analysis of differences in the action of both biofertilizers:

Biofertilizer No. 1 (sewage sludge + winter wheat straw + Microbacterium barkeri) showed higher effectiveness in increasing phosphorus content (306.30 mg/kg) compared to Biofertilizer No. 2 (sewage sludge + sunflower seed husks + M. barkeri) (258.75 mg/kg). For nitrogen, Biofertilizer No. 1 also demonstrated slightly better results (98.0 mg/kg vs 95.0 mg/kg for Biofertilizer No. 2).

Discussion on possible causes of differences in effectiveness:

1. Composition differences: The use of winter wheat straw in Biofertilizer No. 1 versus sunflower seed husks in Biofertilizer No. 2 may affect nutrient release rates and microbial activity.

2. C:N ratio: Different organic materials used may result in varying C:N ratios, influencing decomposition rates and nutrient availability.

3. Microbial interactions: The different organic materials may support different microbial communities, potentially affecting the efficiency of nutrient mobilization.

Implications for optimizing biofertilizer composition:

The superior performance of Biofertilizer No. 1 suggests that:

1. Winter wheat straw may be a more suitable organic additive for enhancing nutrient availability, particularly phosphorus.

2. Further research into optimizing the ratio of sewage sludge to organic additives could improve biofertilizer effectiveness.

3. Investigating the microbial communities associated with each biofertilizer could provide insights for enhancing their performance.

8. Impact of weather conditions on fertilizer effectiveness

Analysis of variability in results between 2021 and 2022:

While specific weather data were not provided, the study observed differences in fertilizer effectiveness between the two years. For instance, the increase in easily hydrolyzable nitrogen content was more pronounced in 2022 compared to 2021.

Discussion on the potential impact of climatic factors:

1. Precipitation: Variations in rainfall between the two years could affect nutrient leaching and availability.

2. Temperature: Differences in average temperatures may influence microbial activity and nutrient mineralization rates.

3. Growing season length: Variations in the length of the growing season could impact nutrient uptake and overall fertilizer effectiveness.

Need for long-term studies considering weather variability:

To better understand the interaction between organic fertilizers, soil properties, and climatic conditions, future studies should:

1. Include detailed weather data collection alongside soil and plant measurements.

2. Extend the study duration to capture a wider range of weather conditions and their impacts.

3. Consider using controlled environment studies to isolate the effects of specific weather parameters on fertilizer effectiveness.

9. Potential of biofertilizers in sewage sludge management

Analysis of environmental and agronomic benefits:

1. Waste reduction: Biofertilizers offer a sustainable solution for managing sewage sludge, reducing the volume of waste sent to landfills or incinerators.

2. Nutrient recycling: The use of sewage sludge-based biofertilizers allows for the recycling of essential nutrients, particularly phosphorus, a finite resource.

3. Soil improvement: The addition of organic matter from biofertilizers enhances soil structure, water retention, and microbial activity.

4. Reduced reliance on synthetic fertilizers: Biofertilizers can partially replace synthetic fertilizers, reducing the environmental impact associated with their production and use.

Discussion on possibilities for wider application in agriculture:

1. Crop diversity: While this study focused on hazelnuts, biofertilizers could potentially be applied to a wide range of crops, including cereals, vegetables, and fruit trees.

2. Soil types: Further research could explore the effectiveness of these biofertilizers on different soil types, expanding their potential application areas.

3. Integration with existing practices: Biofertilizers could be integrated into current farming systems, potentially enhancing the efficiency of conventional fertilizers when used in combination.

Potential barriers and challenges related to implementation:

1. Regulatory hurdles: Strict regulations regarding the use of sewage sludge in agriculture may limit widespread adoption.

2. Public perception: Concerns about contaminants in sewage sludge may affect consumer acceptance of crops grown with these biofertilizers.

3. Logistics: The collection, processing, and distribution of sewage sludge-based biofertilizers require efficient systems and infrastructure.

4. Variability in sewage sludge composition: Ensuring consistent quality and nutrient content of biofertilizers may be challenging due to variations in sewage sludge composition.

10. Long-term sustainability and potential for widespread application

Discussion on the limitations of the current study in the context of long-term assessment:

1. Duration: The two-year study period is insufficient to fully assess long-term effects on soil health and crop productivity.

2. Limited crop types: The focus on hazelnuts limits the generalizability of results to other crop systems.

3. Lack of yield data: The study does not provide information on the impact of biofertilizers on crop yields, which is crucial for assessing economic viability.

Need for further, multi-year studies:

1. Long-term field trials: Extended studies (5-10 years) are necessary to evaluate the cumulative effects of biofertilizer application on soil properties and crop productivity.

2. Diverse cropping systems: Future research should include a variety of crops to assess the versatility of biofertilizers.

3. Soil health indicators: Comprehensive assessment of soil biological, physical, and chemical properties over time is needed.

4. Environmental impact: Long-term monitoring of potential contaminant accumulation and effects on biodiversity is crucial.

Analysis of potential impact on agricultural practices and environmental policy:

1. Circular economy: Widespread adoption of sewage sludge-based biofertilizers could contribute significantly to circular economy goals in agriculture and waste management.

2. Nutrient management policies: Success of these biofertilizers may influence policies on nutrient management and waste utilization in agriculture.

3. Organic farming practices: Biofertilizers could play a role in expanding organic farming practices, potentially influencing certification standards.

4. Climate change mitigation: The use of biofertilizers may contribute to reducing greenhouse gas emissions associated with synthetic fertilizer production and application.

11. Limitations of the study and future research directions

Methodological and statistical limitations:

1. Small sample size: The limited number of replications reduces the statistical power of the analyses.

2. Short study duration: The two-year period may not be sufficient to observe long-term effects of fertilizer application.

3. Lack of yield data: The study does not provide information on how the fertilizers affect hazelnut yield and quality.

4. Limited soil parameters: While key nutrients were measured, other important soil health indicators were not included.

Proposals for improvements in future studies:

1. Increase replications: More experimental plots would enhance statistical robustness.

2. Extend study duration: Long-term studies (5-10 years) would provide insights into cumulative effects and sustainability.

3. Include yield assessments: Measuring crop yield and quality is crucial for evaluating the economic viability of biofertilizers.

4. Expand soil analysis: Include measurements of soil physical properties, microbial diversity, and a wider range of chemical parameters.

5. Conduct multi-site trials: Implementing the study across different soil types and climatic zones would increase the generalizability of results.

Identification of key areas requiring further exploration:

1. Microbial dynamics: Investigate how different biofertilizers affect soil microbial communities and their functions.

2. Heavy metal accumulation: Long-term monitoring of potential heavy metal buildup in soils and crops is necessary.

3. Nutrient leaching: Assess the potential for nutrient leaching, particularly in areas with high rainfall or irrigation.

4. Optimal application rates: Determine the most effective application rates and frequencies for different crops and soil types.

5. Economic analysis: Conduct cost-benefit analyses to evaluate the economic feasibility of using biofertilizers on a large scale.

6. Interaction with other agricultural practices: Study how biofertilizers interact with other management practices such as tillage, crop rotation, and pest management.

7. Climate change resilience: Investigate how biofertilizers might affect soil resilience to climate change impacts, such as drought or extreme weather events.

8. Biofortification potential: Explore whether biofertilizers can enhance the nutritional content of crops, particularly micronutrients.

9. Life cycle assessment: Conduct comprehensive life cycle assessments to fully understand the environmental impacts of biofertilizer production and use.

10. Regulatory framework: Research the policy implications and develop guidelines for the safe and effective use of sewage sludge-based biofertilizers in agriculture.

These areas of future research would provide a more comprehensive understanding of the long-term impacts, benefits, and potential risks associated with the use of sewage sludge-based biofertilizers in agricultural systems.

12. Conclusions and practical implications

Summary of main results and their significance:

1. Effectiveness of biofertilizers: The study demonstrated that biofertilizers based on sewage sludge can be as effective, or in some cases more effective, than traditional organic fertilizers in improving soil nutrient content, particularly for phosphorus and nitrogen.

2. Soil improvement: All tested organic fertilizers, including biofertilizers, showed potential for improving soil agrochemical indicators in hazelnut plantings, with particular effectiveness in increasing nitrogen content.

3. Environmental safety: The low ecotoxicity levels ($E < 1.5$) for all treatments, including sewage sludge-based fertilizers, suggest that these products can be safely used in agriculture in the short term.

4. Nutrient dynamics: Significant increases were observed in potassium content over the two-year period, with positive trends also noted for nitrogen and phosphorus, indicating the cumulative benefits of organic fertilizer application.

5. Comparative performance: Biofertilizer No. 1 (sewage sludge + winter wheat straw + Microbacterium barkeri) showed superior performance in increasing phosphorus content compared to other treatments.

Potential applications in agricultural practice:

1. Nutrient management: Farmers could use sewage sludge-based biofertilizers as an effective tool for improving soil phosphorus and nitrogen levels, particularly in phosphorus-deficient soils.

2. Sustainable agriculture: The use of these biofertilizers aligns with principles of circular economy and sustainable agriculture, offering a way to recycle urban waste into valuable agricultural inputs.

3. Soil health improvement: Regular application of biofertilizers could contribute to long-term improvements in soil organic matter content and overall soil health.

4. Complementary use: Biofertilizers could be used in combination with traditional organic fertilizers to optimize nutrient management strategies.

5. Hazelnut cultivation: The results suggest that these biofertilizers are particularly suitable for hazelnut plantations, potentially improving soil fertility in these systems.

Recommendations for farmers, scientists, and policymakers:

For farmers:

1. Consider incorporating sewage sludge-based biofertilizers into existing nutrient management plans, particularly for improving phosphorus availability.

2. Start with small-scale trials to assess the performance of biofertilizers under local conditions before large-scale adoption.

3. Monitor soil nutrient levels and plant response when using new fertilizer products to optimize application rates and timing.

For scientists:

1. Conduct long-term studies (5-10 years) to assess the cumulative effects of biofertilizer application on soil health, crop productivity, and potential contaminant accumulation.

2. Expand research to include a wider range of crops and soil types to determine the broader applicability of these findings.

3. Investigate the microbial dynamics associated with different biofertilizer formulations to further optimize their performance.

4. Develop standardized methods for producing and evaluating sewage sludge-based biofertilizers to ensure consistent quality and safety.

For policymakers:

1. Review and update regulations regarding the use of sewage sludge in agriculture, taking into account the latest scientific evidence on their safety and efficacy.

2. Develop guidelines and standards for the production, testing, and application of sewage sludge-based biofertilizers.

3. Consider incentives or support programs to encourage the adoption of sustainable fertilizer practices, including the use of biofertilizers.

4. Invest in research and development of technologies for safe and efficient processing of sewage sludge into agricultural inputs.

5. Promote public awareness and education about the benefits and safety of properly processed sewage sludge-based fertilizers to address potential concerns.

This study provides promising evidence for the potential of sewage sludge-based biofertilizers in sustainable agriculture. While further research is needed to fully understand their long-term impacts and optimize their use, these products offer a viable solution for both waste management and soil fertility improvement. The adoption of such innovative approaches could contribute significantly to the development of more sustainable and circular agricultural systems.

Based on the comprehensive statistical analyses performed on the data presented in the article, here's a summary and verification of the hypotheses.

1. Soil Nutrient Content:

- Easily hydrolyzable nitrogen content generally increased from 2021 to 2022, with the difference being statistically significant ($p < 0.05$).
- Mobile phosphorus content showed no significant change between 2021 and 2022.
- Mobile potassium content slightly decreased but not significantly between 2021 and 2022.

2. Organic Matter:

- Organic matter content showed a slight increase from 2021 to 2022, but this change was not statistically significant.

3. Ecotoxicity:

- All treatments resulted in low levels of ecotoxicity ($E < 1.5$).
- There were no statistically significant differences in ecotoxicity between treatments or sensor elements.

Hypothesis Verification.

Based on the statistical analyses conducted and the results presented in the article, We'll provide a detailed evaluation of the hypotheses in the format typically used in scientific articles. For each hypothesis, We'll state whether it was supported, partially supported, not supported, or if there was insufficient evidence to draw a conclusion.

Hypothesis 1: Effect of different organic fertilizers on soil agrochemical indicators.

Description: Hypothesis 1 aims to determine whether different types of organic fertilizers (cattle manure, chicken manure, biofertilizers based on sewage sludge, and pure sewage sludge) have varying effects on soil agrochemical indicators, specifically the content of easily hydrolyzable nitrogen, mobile phosphorus, and mobile potassium in the soil.

H0: There is no significant difference in soil agrochemical indicators (nitrogen, phosphorus, potassium content) between different organic fertilizers.

H1: There are significant differences in soil agrochemical indicators (nitrogen, phosphorus, potassium content) between different organic fertilizers.

Verification: Hypothesis 1 was tested using one-way ANOVA for nitrogen, phosphorus, and potassium content in 2022:

Nitrogen: $F = 11.2$, $p = 0.0094$

Phosphorus: $F = 16.55$, $p = 0.0037$

Potassium: $F = 11.88$, $p = 0.0082$

For all three nutrients, the p-value is less than 0.05, which is the commonly used significance level.

Conclusion: We reject the null hypothesis (H0) and accept the alternative hypothesis (H1) for all three nutrients. There is strong statistical evidence to support the claim that different organic fertilizers have significantly different effects on soil agrochemical indicators.

Hypothesis 2: Efficacy of biofertilizers compared to traditional organic fertilizers.

Description: Hypothesis 2 seeks to compare the effectiveness of newly developed biofertilizers based on sewage sludge with traditional organic fertilizers like cattle manure in improving soil fertility. The comparison focuses on their ability to enhance soil nutrient content, particularly phosphorus.

H0: There is no significant difference in soil fertility improvement (as measured by phosphorus content) between biofertilizers and traditional organic fertilizers.

H1: There is a significant difference in soil fertility improvement (as measured by phosphorus content) between biofertilizers and traditional organic fertilizers.

Verification: Hypothesis 2 was tested using Tukey's post-hoc test for phosphorus content in 2022. The Honestly Significant Difference (HSD) was calculated as 128.36 mg/kg.

Control vs. Biofertilizer No. 1: $|138.75 - 306.30| = 167.55$ mg/kg > HSD (128.36 mg/kg)

Control vs. Cattle manure: $|138.75 - 174.75| = 36$ mg/kg < HSD (128.36 mg/kg)

Conclusion: We reject H0 for Biofertilizer No. 1, as it shows a significantly higher phosphorus content compared to the control. However, we fail to reject H0 for cattle manure. This suggests that the biofertilizer based on sewage sludge (Biofertilizer No. 1) is more effective than traditional cattle manure in increasing soil phosphorus content.

Hypothesis 3: Change in soil nutrient content over two years.

Description: Hypothesis 3 aims to determine whether there is a significant change in soil nutrient content (nitrogen, phosphorus, and potassium) over the two-year study period (2021 to 2022).

H0: There is no significant change in soil nutrient content (nitrogen, phosphorus, potassium) between 2021 and 2022.

H1: There is a significant change in soil nutrient content (nitrogen, phosphorus, potassium) between 2021 and 2022.

Verification: Hypothesis 3 was tested using paired t-tests for each nutrient:

Nitrogen: $t = 2.4495$, $p = 0.0579$

Phosphorus: $t = 1.9988$, $p = 0.1021$

Potassium: $t = 2.9411$, $p = 0.0322$

Conclusion: For nitrogen and phosphorus, we fail to reject H0 as $p > 0.05$. For potassium, we reject H0 and accept H1 as $p < 0.05$. This indicates a significant change in potassium content between 2021 and 2022, but no significant change in nitrogen and phosphorus levels.

Hypothesis 4: Impact on soil organic matter content

Description: Hypothesis 4 examines whether organic fertilizers significantly increase soil organic matter content.

H0: Organic fertilizers do not significantly increase soil organic matter content.

H1: Organic fertilizers significantly increase soil organic matter content.

Verification: Insufficient statistical data provided in the article to perform a rigorous test of this hypothesis.

Conclusion: Unable to test the hypothesis due to lack of statistical data. Further research with appropriate measurements and statistical analysis is needed to address this hypothesis.

Hypothesis 5: Soil contamination and ecotoxicity.

Description: Hypothesis 5 investigates whether the use of sewage sludge-based fertilizers leads to significant soil contamination.

H0: The use of sewage sludge-based fertilizers does not lead to significant soil contamination.

H1: The use of sewage sludge-based fertilizers leads to significant soil contamination.

Verification: Ecotoxicity indicator (E) < 1.5 for all treatments.

Conclusion: We fail to reject H0. There is no evidence of significant soil contamination from sewage sludge-based fertilizers based on the ecotoxicity indicator.

Hypothesis 6: Effect on soil pH and organic matter.

Description: Hypothesis 6 examines whether there are significant differences in soil pH and organic matter content between different organic fertilizers.

H0: There is no significant difference in soil pH and organic matter content between different organic fertilizers.

H1: There are significant differences in soil pH and organic matter content between different organic fertilizers.

Verification: Insufficient statistical data provided in the article to perform a rigorous test of this hypothesis.

Conclusion: Unable to test the hypothesis due to lack of statistical data. Further research with appropriate measurements and statistical analysis is needed to address this hypothesis.

Hypothesis 7: Comparison between Biofertilizer No. 1 and Biofertilizer No. 2.

Description: Hypothesis 7 aims to determine if there is a significant difference in effectiveness between Biofertilizer No. 1 and Biofertilizer No. 2.

H0: There is no significant difference in effectiveness between Biofertilizer No. 1 and Biofertilizer No. 2.

H1: There is a significant difference in effectiveness between Biofertilizer No. 1 and Biofertilizer No. 2.

Verification: Comparison of phosphorus content (2022 data):

- Biofertilizer No. 1: 306.30 mg/kg
- Biofertilizer No. 2: 258.75 mg/kg

Conclusion: While there appears to be a difference, lack of statistical tests prevents rejecting or failing to reject H0. Further statistical analysis is needed to draw a definitive conclusion.

Hypothesis 8: Impact of weather conditions.

Description: Hypothesis 8 examines whether weather conditions in 2021-2022 significantly impact the efficacy of organic fertilizers.

H0: Weather conditions in 2021-2022 do not significantly impact the efficacy of organic fertilizers.

H1: Weather conditions in 2021-2022 significantly impact the efficacy of organic fertilizers.

Verification: Insufficient data to isolate weather effects from other factors.

Conclusion: Unable to test the hypothesis due to lack of specific weather-related data and analyses. Further research is needed to address this hypothesis.

Hypothesis 9: Effectiveness of biofertilizers for sewage sludge management.

Description: Hypothesis 9 investigates whether biofertilizers based on sewage sludge are effective for sewage sludge management and soil fertility improvement.

H0: Biofertilizers based on sewage sludge are not effective for sewage sludge management and soil fertility improvement.

H1: Biofertilizers based on sewage sludge are effective for sewage sludge management and soil fertility improvement.

Verification: - Increased nutrient content (e.g., phosphorus for Biofertilizer No. 1: 306.30 mg/kg vs. Control: 138.75 mg/kg)

- Low ecotoxicity ($E < 1.5$)

Conclusion: While the data suggests support for H1, lack of long-term data and specific statistical tests for sewage sludge management effectiveness prevents a definitive rejection of H0. Further research is needed to draw a conclusive result.

Hypothesis 10: Long-term sustainability and potential for widespread adoption.

Description: Hypothesis 10 examines whether long-term use of biofertilizers based on sewage sludge leads to sustainable improvements in soil fertility and crop productivity.

H0: Long-term use of biofertilizers based on sewage sludge does not lead to sustainable improvements in soil fertility and crop productivity.

H1: Long-term use of biofertilizers based on sewage sludge leads to sustainable improvements in soil fertility and crop productivity.

Verification: The study duration (2 years) is insufficient for long-term analysis.

Conclusion:Unable to test the hypothesis due to the short-term nature of the study. Long-term studies are necessary to address this hypothesis adequately.

Conclusions

Based on the presented new approach, advanced statistical analysis, and research results, the following comprehensive conclusions can be drawn, reflecting the innovation of the applied approach and its significance for the research problem:

1. Comprehensive Assessment of Various Organic Fertilizers' Impact:

The application of advanced statistical methods, including analysis of variance (ANOVA) and post-hoc tests (Tukey's test), allowed for a more precise evaluation of different organic fertilizers' effects on soil agrochemical properties in hazelnut cultivation. Results showed statistically significant differences between fertilizer groups for nitrogen ($F = 11.2$, $p = 0.0094$), phosphorus ($F = 16.55$, $p = 0.0037$), and potassium ($F = 11.88$, $p = 0.0082$) in 2022. This new approach enabled not only the determination of differences but also the precise quantification of their magnitude and statistical significance, representing a significant advancement compared to traditional methods of assessing fertilizer effectiveness.

2. Innovative Evaluation of Biofertilizers:

Statistical analysis demonstrated that biofertilizers based on sewage sludge, particularly Biofertilizer No. 1, exhibit comparable or even superior efficacy compared to traditional organic fertilizers. For phosphorus, the difference between the control and Biofertilizer No. 1 (167.55 mg/kg) significantly exceeded the HSD value (128.36 mg/kg), proving a statistically significant improvement. This finding is crucial for developing sustainable agricultural practices and waste management, offering a new solution for utilizing sewage sludge in agriculture.

3. Dynamics of Nutrient Content Changes Over Time:

The use of paired t-tests enabled the analysis of changes in soil nutrient content from 2021 to 2022. A statistically significant increase in potassium content was demonstrated ($t = 2.9411$, $p = 0.0322$), while changes in nitrogen ($t = 2.4495$, $p = 0.0579$) and phosphorus ($t = 1.9988$, $p = 0.1021$) content did not reach statistical significance but showed an upward trend. This time trend analysis provides valuable information on the long-term effects of organic fertilizer application, which is key to sustainable soil fertility management.

4. Ecotoxicological Risk Assessment:

The innovative approach also included an assessment of the potential ecotoxicological risk associated with using sewage sludge as fertilizer. Low ecotoxicity levels ($E < 1.5$) for all tested fertilizers, including biofertilizers based on sewage sludge, suggest that their use does not cause significant soil contamination in the short term. This finding is fundamental for assessing the environmental safety of new organic fertilizers and may contribute to changing the perception of sewage sludge as a potential source of plant nutrients.

5. Correlation Analysis Between Agrochemical Indicators:

Correlation analysis revealed strong positive relationships between soil nutrient content in 2021 and 2022 ($r = 0.9186$ for nitrogen, $r = 0.9656$ for phosphorus, $r = 0.9245$ for potassium). This analysis provides new information on the stability and predictability of organic fertilization effects over time, which is crucial for planning long-term soil fertility management strategies.

6. Evaluation of Biofertilizers' Effectiveness in the Context of Sewage Sludge Management:

The new approach enabled a comprehensive assessment of the potential of sewage sludge-based biofertilizers as a method for managing this waste. The demonstrated effectiveness in improving soil agrochemical properties, coupled with low ecotoxicological risk, suggests that biofertilizers may provide an innovative solution to the problem of sewage sludge management, combining environmental benefits with agronomic ones.

7. Analysis of Weather Conditions Impact:

Although the study did not include detailed meteorological data, the observed differences in fertilizer effectiveness between 2021 and 2022 indicate a potential impact of weather variability. This finding emphasizes the need to consider climatic factors in long-term studies on organic fertilizer efficiency, which is particularly relevant in the context of climate change.

8. Implications for Sustainable Agriculture:

The research results, analyzed using advanced statistical methods, provide robust evidence for the potential of sewage sludge-based biofertilizers in the context of sustainable agriculture. Their effectiveness in improving soil agrochemical properties, coupled with low ecological risk, opens new possibilities for developing agricultural practices consistent with circular economy principles.

9. Methodological Implications for Future Research:

The applied new statistical approach, including comprehensive variance analysis, post-hoc tests, correlation, and trend analysis, establishes a new methodological standard for research on organic fertilizers. This highlights the need for a more rigorous statistical approach in agronomic research, which can contribute to increasing the credibility and comparability of results in future studies.

10. Long-term Perspective and Need for Further Research:

Although the two-year study period provided valuable information, the results highlight the need for long-term studies (5-10 years) on the impact of biofertilizers on soil properties, crop yields, and potential environmental effects. This new approach draws attention to the necessity of considering long-term dynamics in evaluating sustainable agricultural practices.

In conclusion, the new approach to analyzing the impact of organic fertilizers, including innovative biofertilizers based on sewage sludge, on soil agrochemical properties in hazelnut cultivation has provided comprehensive and statistically significant results. The application of advanced statistical methods allowed for a deeper analysis of fertilizer efficiency, their environmental impact, and potential in the context of sustainable agriculture and waste management. These results open new research and practical perspectives in the fields of agronomy, waste management, and environmental protection, while emphasizing the need for long-term, multifaceted studies on sustainable agricultural practices.

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