НАУКОВІ ГОРИЗОНТИ

УДК 63

Редакція, видавець:
Поліський національний університет
Рік заснування: 1998
Періодичність випуску: 4 рази на рік

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Поліського національного університету
(протокол № 8 від 25 березня 2026 року)

Рішення національної ради України
з питань телебачення і радіомовлення № 1533.
Ідентифікатор медіа – R30-01593

Науковий журнал включено до категорії Б Переліку наукових фахових видань України, у яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора та кандидата ветеринарних, економічних, сільськогосподарських і технічних наук зі спеціальностей: 051 – Економіка; 071 – Облік і оподаткування; 072 – Фінанси, банківська справа та страхування; 073 – Менеджмент; 075 – Маркетинг; 076 – Підприємництво, торгівля та біржова діяльність; 101 – Екологія; 133 – Галузеве машинобудування; 201 – Агрономія; 202 – Захист і карантин рослин; 203 – Садівництво та виноградарство; 204 – Технологія виробництва і переробки продукції тваринництва; 205 – Лісове господарство; 206 – Садово-паркове господарство; 208 – Агроінженерія; 211 – Ветеринарна медицина (наказ МОН України № 1693 від 23 грудня 2025 р.)

Кластер – Сільськогосподарські і ветеринарні науки

Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах: Інституційний репозитарій Поліського національного університету, AGRICOLA, CAB Abstracts and Global Health (CABI), Реєстр наукових видань України, Національна бібліотека України імені В. І. Вернадського, Crossref, ERIH PLUS, International System for Agricultural Science and Technology (AGRIS), Dimension, Polska Bibliografia Naukowa, Google Scholar, Ulrichsweb Global Serials Directory, UCSB Library, EBSCO, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, OUCI (Open Ukrainian Citation Index), Worldcat, CORE, COPE, Litmaps

Адреса редакції:
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/uk

SCIENTIFIC HORIZONS

UDC 63

Editorial and Publisher:
Polissia National University

Year of foundation: 1998
Frequency of issue: 4 issues per year

Recommended for printing and distribution
via the Internet by the Academic Council
of Polissia National University
(Minutes No. 8 of March 25, 2026)

Decision of the National Council
of Television and Radio Broadcasting of Ukraine No. 1533.
Media identifier – R30-01593

The scientific journal is included in category B of the List of scientific professional publications of Ukraine, in which the results of dissertations for the degree of doctor and candidate of veterinary, economic, agricultural, and technical sciences can be published in the following specialties: 051 – Economy; 071 – Accounting and Taxation; 072 – Finance, Banking and Insurance; 073 – Management; 075 – Marketing; 076 – Entrepreneurship, Trade and Exchange Activities; 101 – Ecology; 133 – Sectoral Engineering; 201 – Agronomy; 202 – Plant Protection and Quarantine; 203 – Horticulture and Viticulture; 204 – Technology of Production and Processing of Livestock Products; 205 – Forestry; 206 – Park and Gardening Management; 208 – Agricultural Engineering; 211 – Veterinary Medicine
(Order of the Ministry of Education and Science of Ukraine No. 1693 of December 23, 2025)

Cluster – Agricultural and Veterinary Sciences

The journal is presented international scientometric databases, repositories and scientific systems: Institutional Repository of Polissia National University, AGRICOLA, CAB Abstracts and Global Health (CABI), Register of Scientific Publications of Ukraine, Vernadsky National Library of Ukraine, Crossref, ERIH PLUS, International System for Agricultural Science and Technology (AGRIS), Dimension, Polska Bibliografia Naukowa, Google Scholar, Ulrichsweb Global Serials Directory, UCSB Library, EBSCO, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, OUCI (Open Ukrainian Citation Index), Worldcat, CORE, COPE, Litmaps

Editors office address:
Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/en

НАУКОВІ ГОРИЗОНТИ

Том 29, № 1
2026

НАУКОВИЙ ЖУРНАЛ
Засновано 12 березня 1998 р.
Періодичність випуску: чотири рази на рік

Редакційна колегія

Головний редактор

Олег Васильович Скидан	Доктор економічних наук, професор, ректор, Поліський національний університет, Україна

Заступник головного редактора

Тетяна Федонюк	Доктор сільськогосподарських наук, професор, Поліський національний університет, Україна

Національні члени редколегії

Іван Грабар	Доктор технічних наук, професор, Поліський національний університет, Україна
Наталія Сорока	Доктор ветеринарних наук, професор, Національний університет біоресурсів і природокористування України, Україна
Руслана Ставецька	Доктор сільськогосподарських наук, професор, Білоцерківський національний аграрний університет, Україна
Анастасія Зимароєва	Кандидат біологічних наук, доцент, Поліський національний університет, Україна
Людмила Чижевська	Доктор економічних наук, професор, Державний університет «Житомирська політехніка», Україна
Віталій Данкевич	Доктор економічних наук, професор, Поліський національний університет, Україна
Ельчин Алієв	Доктор технічних наук, професор, Дніпровський державний аграрно-економічний університет, Україна
Олександр Галатюк	Доктор ветеринарних наук, професор, Поліський національний університет, Україна
Валентина Гамаюнова	Доктор сільськогосподарських наук, професор, Миколаївський національний аграрний університет, Україна
Леонід Горальський	Доктор ветеринарних наук, професор, Житомирський державний університет імені Івана Франка, Поліський національний університет, Україна
Дмитро Дерев'янко	Доктор технічних наук, професор, Поліський національний університет, Україна
Олександр Жуков	Доктор біологічних наук, професор, Мелітопольський державний педагогічний університет імені Богдана Хмельницького, Україна
Ірина Іванова	Кандидат сільськогосподарських наук, доцент, Таврійський державний агротехнологічний університет ім. Д. Моторного, Україна
Олександр Кочук-Ященко	Кандидат сільськогосподарських наук, доцент, Поліський національний університет, Україна
Дмитро Кучер	Кандидат сільськогосподарських наук, доцент, Поліський національний університет, Україна
Федір Марков	Кандидат сільськогосподарських наук, доцент, Поліський національний університет, Україна
Олена Марковська	Доктор сільськогосподарських наук, старший науковий співробітник, Херсонський державний аграрно-економічний університет, Україна
Андрій Михайлов	Доктор економічних наук, професор, Сумський національний аграрний університет, Україна

Валентин Москалець	Доктор сільськогосподарських наук, доцент, Інститут садівництва НААН, Україна
Віктор Пазич	Кандидат сільськогосподарських наук, доцент, Поліський національний університет, Україна
Людмила Тарасович	Кандидат економічних наук, доцент, Поліський національний університет, Україна
Тетяна Тимощук	Кандидат сільськогосподарських наук, доцент, Поліський національний університет, Україна
Наталія Цивенкова	Кандидат технічних наук, доцент Національний університет біоресурсів і природокористування України, Поліський національний університет, Україна
Марина Швець	Кандидат біологічних наук, старший викладач, Поліський національний університет, Україна
Тетяна Зінчук	Доктор економічних наук, професор, Поліський національний університет, Україна
Геннадій Голуб	Доктор технічних наук, професор, Національний університет біоресурсів і природокористування України, Україна

Міжнародні члени редколегії

Савелій Кухарець	Доктор технічних наук, професор, Університет Вітовта Великого, Литва
Юліус Раманаускас	Доктор наук, професор, Клайпедський університет, Литва
Інна Левкович	Доктор наук, старший науковий співробітник, Лейбніцький інститут розвитку сільського господарства у країнах з перехідною економікою, Німеччина
Егідіюс Сараускіс	Доктор технічних наук, професор, Інститут сільськогосподарської техніки та безпеки університету Вітовта Великого, Литва
Ришард Пукала	Кандидат економічних наук, Державний Техніко-Економічний Університет ім. кс. Броніслава Маркевича в Ярославі, Польща
Самат Танірбергенов	Вчений секретар, Казахський науково-дослідний інститут ґрунтознавства і агрохімії ім. У.У. Успанова, Республіка Казахстан
Шпенд Шахіні	Кандидат наук у галузі захисту рослин, Сільськогосподарський університет Тирани, Албанія
Фатбард Саллаку	Кандидат наук у галузі захисту рослин, ректор Сільськогосподарського університету Тирани, Албанія

SCIENTIFIC HORIZONS

Vol. 29, No. 1
2026

SCIENTIFIC JOURNAL
Year of establishment: Since March 1998.
Publication frequency: Four times a year

Editorial Board

Editor-in-Chief

Oleh Skydan	Doctor of Economic Sciences, Professor, Rector, Polissia National University, Ukraine

Deputy Editor-in-Chief

Tatiana Fedoniuk	Doctor of Agricultural Sciences, Professor, Polissia National University, Ukraine

National Members of the Editorial Board

Ivan Grabar	Doctor of Technical Sciences, Professor, Polissia National University, Ukraine
Natalia Soroka	Doctor of Veterinary Sciences, Professor, National University of Life and Environmental Sciences of Ukraine, Ukraine
Ruslana Stavetska	Doctor of Agricultural Sciences, Professor, Bila Tserkva National Agrarian University, Ukraine
Anastasiia Zymaroieva	PhD in Biological Sciences, Associate Professor, Polissia National University, Ukraine
Lyudmyla Chyzhevska	Doctor of Economic Sciences, Professor, Zhytomyr Polytechnic State University, Ukraine
Vitalii Dankevych	Doctor of Economic Sciences, Professor, Polissia National University, Ukraine
Elchin Aliiev	Doctor of Technical Sciences, Professor, Dnipro State Agrarian and Economic University, Ukraine
Olexandr Galatiuk	Doctor of Veterinary Sciences, Professor, Polissia National University, Ukraine
Valentina Hamaiunova	Doctor of Agricultural Sciences, Professor, Mykolaiv National Agrarian University, Ukraine
Leonid Goralskiy	Doctor of Veterinary Sciences, Professor, Zhytomyr Ivan Franko State University, Polissia National University, Ukraine
Dmytro Derevjanko	Doctor of Technical Sciences, Professor, Polissia National University, Ukraine
Olexander Zhukov	Doctor of Biological Sciences, Professor, Bogdan Khmelnitsky Melitopol State Pedagogical University, Ukraine
Iryna Ivanova	PhD in Agricultural Sciences, Associate Professor, Dmytro Motornyi Tavria State Agrotechnological University, Ukraine
Oleksandr Kochuk-Yashchenko	PhD in Agricultural Sciences, Associate Professor, Polissia National University, Ukraine
Dmytro Kucher	PhD in Agricultural Sciences, Associate Professor, Polissia National University, Ukraine
Fedir Markov	PhD in Agricultural Sciences, Associate Professor, Polissia National University, Ukraine
Olena Markovska	Doctor of Agricultural Sciences, Senior Research Scientist, Kherson State Agrarian and Economic University, Ukraine
Andrii Mykhailov	Doctor of Economic Sciences, Professor, Sumy National Agrarian University, Ukraine
Valentyn Moskalets	Doctor of Agricultural Sciences, Associate Professor, Institute of Horticulture of the National Academy of Agrarian Sciences, Ukraine
Viktor Pazych	PhD in Agricultural Sciences, Associate Professor, Polissia National University, Ukraine
Ludmyla Tarasovych	PhD in Economic Sciences, Associate Professor, Polissia National University, Ukraine
Tetiana Tymoshchuk	PhD in Agricultural Sciences, Associate Professor, Polissia National University, Ukraine

Natalia Tsyvenkova	PhD in Technical Sciences, Associate Professor, National University of Life and Environmental Sciences of Ukraine, Polissia National University, Ukraine
Marina Shvets	PhD in Biological Sciences, Senior Teacher, Polissia National University, Ukraine
Tetyana Zinchuk	Doctor of Economic Sciences, Professor, Polissia National University, Ukraine
Gennadii Golub	Doctor of Technical Sciences, Professor, National University of Life and Environmental Sciences of Ukraine, Ukraine

International members of the Editorial Board

Savelli Kukharets	Doctor of Technical Sciences, Professor, Vytautas Magnus University, Lithuania
Julius Ramanauskas	Doctor Habilitatus, Professor, Klaipeda University, Lithuania
Inna Levkovych	Doctor Habilitatus, Senior Research Scientist, Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Germany
Egidijus Sarauskis	Doctor of Technical Sciences, Professor, Institute of Agricultural Engineering and Safety of Vytautas Magnus university (VMU), Lithuania
Ryszard Pukala	PhD in Economic Sciences, the Bronisław Markiewicz State University of Technology and Economics in Jarosław, Poland
Samat Tanirbergenov	Scientific Secretary, U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistrydis, Republic of Kazakhstan
Shpend Shahini	PhD in Plant Protection, Agricultural University of Tirana, Albania
Fatbardh Sallaku	PhD in Plant Protection, Rector of the Agricultural University of Tirana, Albania

ЗМІСТ

CONTENTS

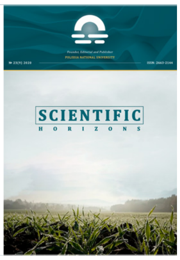
ISSN 2663-2144 e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 29(1), 9-19

UDC 633.2.03:631.8 DOI: 10.48077/scihor1.2026.09



Assessment of the impact of the component composition of grass mixtures on the productivity of sown agrocenoses in the Precarpathian region

Nataliya Karasevych*
PhD, Senior Researcher
Institute of Agriculture of Carpathian Region of the National Academy of Sciences of Ukraine
81115, 5 Hrushevskyi Str., Obroshyne Village, Ukraine
https://orcid.org/0000-0002-1416-559X

Taras Martsinko
PhD in Agricultural Sciences, Leading Research Fellow
Institute of Agriculture of Carpathian Region of the National Academy of Sciences of Ukraine
81115, 5 Hrushevskyi Str., Obroshyne Village, Ukraine
https://orcid.org/0000-0002-6912-420X

Liubomyr Buhryn
PhD in Agricultural Sciences, Senior Researcher
Institute of Agriculture of Carpathian Region of the National Academy of Sciences of Ukraine
81115, 5 Hrushevskyi Str., Obroshyne Village, Ukraine
https://orcid.org/0000-0001-6180-203X

Andrii Dzubaylo
Doctor of Agricultural Sciences, Leading Research Fellow
Institute of Agriculture of Carpathian Region of the National Academy of Sciences of Ukraine
81115, 5 Hrushevskyi Str., Obroshyne Village, Ukraine
https://orcid.org/0000-0002-1309-6924

Stepan Begey
PhD in Agricultural Sciences, Leading Research Fellow
Institute of Agriculture of Carpathian Region of the National Academy of Sciences of Ukraine
81115, 5 Hrushevskyi Str., Obroshyne Village, Ukraine
https://orcid.org/0000-0002-7193-0550

Article's History:
Received: 12.11.2025
Revised: 26.02.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. This study aimed to determine the effect of the component composition of perennial grass mixtures on the productivity of sown agrocenoses under the soil and climatic conditions of the Precarpathian region. Field experiments were conducted in 2020-2024 on sod-podzolic soils, using a summer sowing method without a cover crop and applying mineral fertilisers at a rate of $N_{30}P_{60}K_{90}$, following the methodological recommendations of the National Academy of Agrarian Sciences of Ukraine. Yield was assessed using the plot-by-weight method; the content of absolutely dry matter was

Suggested Citation:
Karasevych, N., Martsinko, T., Buhryn, L., Dzubaylo, A., & Begey, S. (2026). Assessment of the impact of the component composition of grass mixtures on the productivity of sown agrocenoses in the Precarpathian region. *Scientific Horizons*, 29(1), 9-19. doi: 10.48077/scihor1.2026.09.

*Corresponding author

determined by drying samples at 105°C; and the botanical composition of the stands was analysed based on selective samples of green mass. The results showed that the highest productivity was achieved with multi-component grass mixtures comprising both grass and legume species. An optimal balance of components in the mixtures had a positive effect on dry matter yield, energy efficiency, and stand resilience. The generalised findings indicated that the inclusion of legumes – particularly red clover (*Trifolium pratense*), alfalfa (*Medicago sativa*), and common bird's-foot trefoil (*Lotus corniculatus*) – increased yield by 30%-45% compared with monoculture sowings. The dynamics of changes in botanical composition over three cuts were analysed. It was found that multi-component mixtures formed a more stable stand structure and ensured a higher proportion of legume components in the second and third cuts. An energy assessment confirmed the feasibility of using mixed sowings due to their higher energy return ratio. The findings can be applied by agronomists, fodder production specialists, and practitioners of ecosystem-based farming to establish highly productive and stable stands in the Precarpathian region

Keywords: crop yield; dry matter content; botanical composition of grass stand; grass mixtures; energy efficiency

INTRODUCTION

Ukrainian agriculture, like most other sectors of the economy, has been affected by the financial crisis and the country's challenging economic situation. Fodder is one of the key resources for livestock farming, making it essential to establish cultivated meadows capable of providing highquality, affordable, and readily available feed, as noted by H. Panakhyd *et al.* (2020). This necessity encourages the search for alternative methods of increasing crop productivity, such as the use of low rates of mineral fertilisers and the fullest exploitation of their biological potential. Particular attention is given to selecting the optimal composition of grass mixtures and applying fertilisers that stimulate plant growth and development, thereby enhancing both yield and quality. According to the research of T. Martsinko (2020), it is especially important to study the formation processes of sown legume-grass stands, particularly their development patterns, and to subsequently design methods aimed at improving their resilience and productivity. This can be achieved by improving the composition of grass mixtures and optimising the fertilisation system for sown meadow ecosystems. Since mineral fertilisers are seldom applied to meadows, or not used at all, due to their high cost, a key factor in increasing hayfield productivity is biological nitrogen fixed by leguminous grasses. Its utilisation significantly improves the environmental situation, as it does not leach into groundwater, accumulate in water bodies, pollute the air, or disrupt the soil's biological balance. According to U. Karbivska *et al.* (2020), incorporating legumes into legume-grass mixtures can increase the yield of sown meadowlands considerably – by 1.5-2 times. Moreover, it contributes to improved fodder quality and enhanced soil fertility.

In fodder production, various approaches and principles are used to select species for grass mixtures. However, under current conditions, these methods do not always align with practical requirements, as they often overlook allelopathic interactions between plants. This means that one species may inhibit the growth and development of another, which can affect the objectivity of species selection for mixtures. The competitiveness of different perennial grass species may vary considerably depending on environmental factors and management regimes. As noted by M. Komainda *et al.* (2019), the establishment of productive meadows is best achieved using perennial grass mixtures that provide higher and more stable yields compared with monocultures of grass or legumes. Through the careful selection of grass mixtures, it is possible to maintain high land productivity over an extended period. According to V. Petrychenko *et al.* (2020), the proper choice of grasses is a key factor in forming mixtures, as it determines not only the species composition but also the chemical characteristics and nutritional value of the fodder. Plants continuously influence the environment in which they grow, leading to interactions between them. The main factors driving these interactions are competition for nutrients, moisture, and light, as well as the decomposition of dead plant residues – a process that can be accelerated through liming and fertilisation. The impact of plants and the correction of the botanical composition of plant communities can be managed by purposefully altering environmental conditions.

The Precarpathian zone, where the research was conducted, is characterised by adequate moisture levels and an undulating landscape, creating favourable conditions for the development of meadow-based fodder production. High stand productivity is achievable with the correct selection of species composition, adherence to appropriate utilisation periods, and proper maintenance. However, the interactions between individual grass species in the process of nutrient uptake have not been fully studied. In particular, competition and the viability of certain species in mixed sowings remain insufficiently explored. This is especially relevant for grass and legume grasses in sown cenoses, where their interrelations require further investigation. In light of the above, it is important to identify the patterns of formation of highly productive sown stands with legume-grass components under varying proportions of perennial legumes in the grass mixtures, as well as to develop effective measures for maintaining legume species in the meadow phytocoenoses of the Precarpathian region. This study aimed, therefore, to analyse the effect of grass mixture components on the productivity of sown agrocenoses in the foothills of the Precarpathian region, and to develop effective methods for forming balanced stands with due consideration of the proportion of legume components.

LITERATURE REVIEW

In the early stages of field cultivation, perennial grasses were largely sown as monocultures. However, it was later established that mixtures containing three or four components have advantages over single-species sowings. V. Petrychenko *et al.* (2020) report that grass-legume mixtures produce yields 19%-20% higher than those of monocultures of grasses. Increasing the area under perennial legume crops not only optimises livestock rations during the transitional period but also ensures the production of high-protein winter fodder in the form of hay and silage. To achieve high productivity, it is essential to select grass species suited to the soil and climatic conditions of the specific growing zone. Research by B. de Haas *et al.* (2019) demonstrated that legume-grass mixtures utilise solar energy more efficiently and contribute to improving soil quality. Grass plants mainly absorb nutrients from the upper soil layers, requiring less phosphorus, potassium, and calcium than legumes, which take up these elements primarily from the arable and subsoil layers. Grass-legume mixtures also have a more efficient leaf arrangement and a greater total leaf area, which enhances the uptake of carbon dioxide from the air through the use of solar energy.

A grass mixture is a purposefully selected combination of different populations, species, and varieties of grasses that develop according to principles different from those of monocultures. Each population within such a sowing supports the existence of the others. Changes in the abundance or biomass of one population lead to adjustments in the other components of the mixture. A. Dziubailo & N. Pylypiv (2022) noted that each population must be provided with conditions that will ensure the highest possible yield of the entire mixture throughout its period of use. The most common species in the stand of meadows and pastures are grasses of the family *Poaceae* (*Graminae*). Timothy is regarded as one of the most productive and nutritious grasses. It is widely used in the formation of cultivated pastures, both in mixtures and as a sole crop. It thrives on meadows and in arable crop rotations, with hay yields reaching up to 8 t/ha. Another highly productive species is tall fescue, noted for its high frost resistance and tolerance to drought. In terms of both fodder quality and yield, tall fescue is among the most productive cultivated perennial grasses, producing 6-10 t/ha of hay. For fodder purposes, it is sown in mixtures with legumes and other grasses when used for cutting.

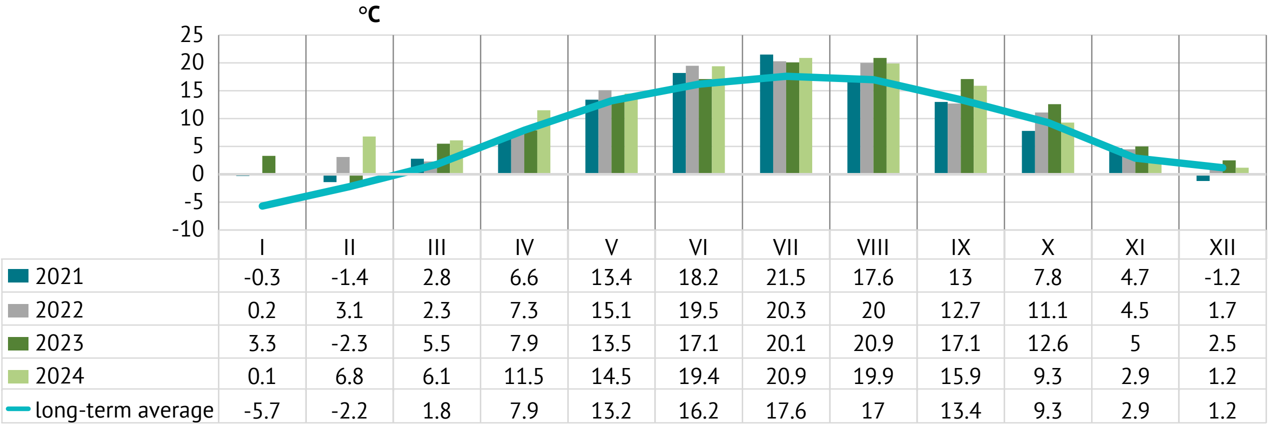
M. Monjardino *et al.* (2022), H. Zhang *et al.* (2022), and others have reported that perennial legume crops have a positive effect on the physico-chemical properties of the soil, contributing to structural restoration, preventing erosion, and strengthening the fodder base. They also play an important role in stabilising agricultural production. Y. Zhang *et al.* (2024) noted that the careful selection of grass crops for cultivation in combination with alfalfa, red clover, and other legumes enables the optimal use of their biological traits while taking account of soil and climatic conditions. Alfalfa is considered an essential component of grass mixtures intended for use in hayfields and pastures. According to P. Patra & T. Paul (2021), Y. Feng *et al.* (2022), it is the most versatile forage crop, characterised by high yield, multiple cutting potential, longevity, and adaptability to a wide range of growing conditions. It provides a consistent yield of green biomass and is widely utilised in the agricultural sector. Its lifespan in cropping can reach 10-25 years, with economic use typically lasting up to eight years. Due to its rapid regrowth, alfalfa can produce three to four cuts per season. From the second or third year of growth, the nitrogen accumulation in the soil is equivalent to applying 40-60 t/ha of manure. The decomposition of alfalfa's organic residues contributes to humus formation, improving soil fertility, reducing acidity, and enhancing both water and air permeability. Its deep root system aids in improving soil structure, increasing humus content, and serving as a natural phytosanitary barrier due to its resistance to pests and diseases.

V. Kurhak & U. Karbivska (2020) note that clover and alfalfa are the leading leguminous forage crops in Ukraine. Red clover is distinguished by its high content of protein, vitamins (E, B1, B2, B3, C, D, K), carotene, and micronutrients (molybdenum, copper, manganese, cobalt, boron). It is used for the production of hay, silage, and grass meal. For example, 100 kg of silage contains 3,842 feed units and up to 5.5 kg of digestible protein, while grass meal contains twice as much digestible protein as hay. From 1 ha of soil (0-30 cm), 6.02 t of air-dry residues are produced. Clover tolerates cold well, germinating at just 2°C, with optimal emergence at 10°C-15°C. The best time for hay harvesting is at the onset of flowering, when protein and vitamin levels are at their peak. Delayed harvesting results in leaf loss and reduced nutritive value. Thus, as reported in numerous studies, multi-component grass mixtures based on grasses and legumes offer significant agronomic and fodder advantages over monocultures. Their effectiveness largely depends on the careful selection of species suited to the soil and climatic conditions, which not only increases productivity but also enhances the ecological sustainability of agroecosystems.

MATERIALS AND METHODS

The experimental work was carried out in 2021-2024 at the Precarpathian Department of Scientific Research of the Institute of Agriculture in the Carpathian region, National Academy of Agrarian Sciences of Ukraine (NAAS), in the village of Lishnia, Drohobych District, Lviv Region. The trial was established using a coverless sowing method on 16 July 2020 on sod-podzolic, surface-gleyed, moderately acidic loamy soils. Agronomic practices followed generally accepted standards (Ushkarenko *et al.,* 2014), with the exception of the experimental variables under investigation. Three cuts were taken each year at the beginning of the flowering stage of the grasses, except in the establishment year, when crop formation was incomplete and only one cut was possible. The experimental design included the following treatments: Variant 1 – timothy; Variant 2 – timothy + red clover; Variant 3 – timothy + alfalfa; Variant 4 – timothy + common bird's-foot trefoil; Variant 5 – timothy + red clover + alfalfa + common bird's-foot trefoil; Variant 6 – timothy + perennial ryegrass + tall fescue+ red clover + common bird's-foot trefoil+ alfalfa.

The study used varieties of perennial grasses listed in the State Register of Plant Varieties Suitable for Distribution in Ukraine (2025), namely: timothy (Podhiryanka), tall fescue (Smerichka), perennial ryegrass (Drohobytskyi 16), red clover (Precarpathian 6), alfalfa (Syniukha), and common bird's-foot trefoil (Ajax). The proportion of leguminous to grass crops was 40% to 60%, respectively. Each spring, prior to the start of growth, all experimental variants received mineral fertilisers at a rate of $N_{30}P_{60}K_{90}$. All research activities were conducted per the methodological guidelines of the Institute of Feed Research of NAAS (Babych *et al.,* 1998). Figures 1 and 2 present the meteorological data for the growing seasons of 2021-2024, based on observations from the Drohobych meteorological station. Comparing the average monthly air temperatures and total precipitation with long-term averages allows the identification of trends and anomalies affecting vegetation conditions.



	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2021	-0.3	-1.4	2.8	6.6	13.4	18.2	21.5	17.6	13	7.8	4.7	-1.2
2022	0.2	3.1	2.3	7.3	15.1	19.5	20.3	20	12.7	11.1	4.5	1.7
2023	3.3	-2.3	5.5	7.9	13.5	17.1	20.1	20.9	17.1	12.6	5	2.5
2024	0.1	6.8	6.1	11.5	14.5	19.4	20.9	19.9	15.9	9.3	2.9	1.2
long-term average	-5.7	-2.2	1.8	7.9	13.2	16.2	17.6	17	13.4	9.3	2.9	1.2

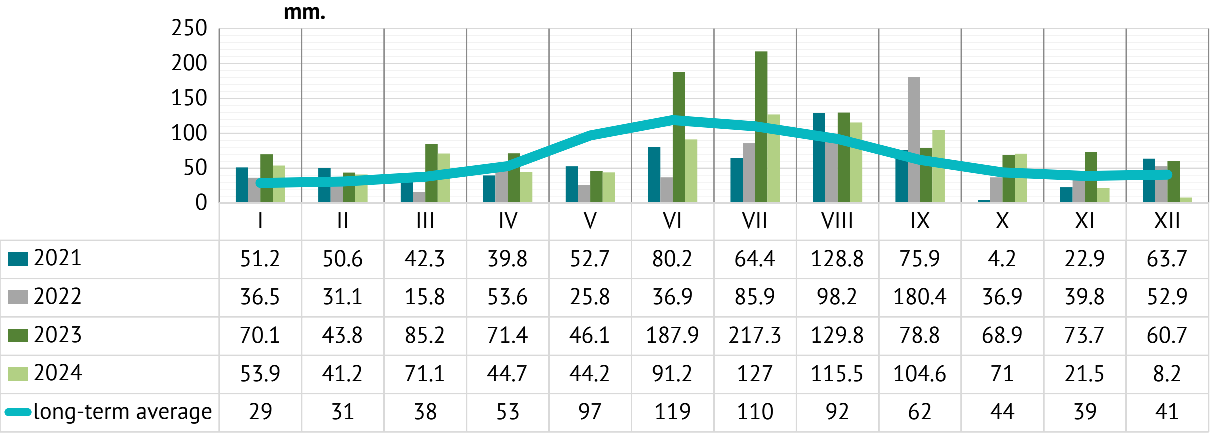
Figure 1. *Monthly temperature distribution during the growing seasons of 2021-2024*

Source: *developed by the authors*

During 2021-2024, air temperatures in all months of the growing season were, on average, higher than long-term average values. In 2021, for instance, June and July recorded temperatures exceeding the norm by 2°C-4°C. The average temperature in July 2021 reached 21.5°C, considerably above the long-term average. In 2022, temperatures were also elevated, particularly in May, when the average value was 1.9°C higher than the norm. The year 2023 was marked by certain temperature fluctuations, yet overall values remained above the long-term average, especially in March and May. In 2024, the temperature in April (11.5°C) was 3.6°C higher than the long-term average, indicating a continuing warming trend. July 2024 also experienced elevated temperatures, reaching 20.9°C, which is 3.3°C above the long-term average.

Precipitation totals showed considerable annual variation. In 2021, June and July recorded significantly higher rainfall than the long-term averages, with 119 mm in June and 110 mm in July. In 2022, the greatest deviation occurred in May, when total rainfall was only 25.8 mm, well below the norm of 97 mm. August 2022, however, received more precipitation than the long-term average, at 98.2 mm. In 2023, July was the wettest month across all years considered, with rainfall reaching 217.3 mm, nearly twice the average. July 2024 also saw high precipitation (127 mm), while August remained closer to the long-term average (115.5 mm). During the autumn-winter period (September-December) from 2021 to 2024, notable fluctuations were observed in both temperature and rainfall. In September, average temperatures ranged from 13.0°C to 17.1°C, exceeding the long-term average values. In October, temperatures ranged from 7.8°C to 12.6°C, in November from 2.9°C to 4.7°C, and in December from -1.2°C to 2.5°C. The highest temperatures in November and December were recorded in 2021 and 2023, respectively.

Regarding precipitation, September totals varied from 78.8 mm (2023) to 180.4 mm (2022). In October, rainfall ranged from 4.2 to 68.9 mm. November generally experienced moderate precipitation (21.5-39.8 mm), except in 2023, when rainfall exceeded the long-term average by 34.7 mm, while December precipitation ranged from 8.2 to 63.7 mm, peaking in 2021. These weather patterns indicate a trend towards a mild autumn with elevated temperatures and variable rainfall, as well as gradual warming during the winter period (Fig. 2).



	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
■ 2021	51.2	50.6	42.3	39.8	52.7	80.2	64.4	128.8	75.9	4.2	22.9	63.7
■ 2022	36.5	31.1	15.8	53.6	25.8	36.9	85.9	98.2	180.4	36.9	39.8	52.9
■ 2023	70.1	43.8	85.2	71.4	46.1	187.9	217.3	129.8	78.8	68.9	73.7	60.7
■ 2024	53.9	41.2	71.1	44.7	44.2	91.2	127	115.5	104.6	71	21.5	8.2
━ long-term average	29	31	38	53	97	119	110	92	62	44	39	41

***Figure 2**. Monthly distribution of precipitation during the growing seasons of 2021-2024*

***Source:** developed by the authors*

Overall, the data indicate a steady increase in air temperatures during the growing season over recent years, suggesting a trend towards global warming that affects agronomic conditions for crop cultivation. Additionally, the changing precipitation regime, characterised by uneven monthly distribution, necessitates the adaptation of agronomic practices to maintain stable yields. Considering these factors, agricultural management methods must be adjusted to respond to evolving climatic conditions.

Based on the analysis of precipitation, considerable variability can be observed, particularly during the summer months, when rainfall totals often exceeded long-term averages, indicating an increase in the frequency of intense rainfall events. This can affect the water supply available to crops, necessitating adjustments to agronomic practices to ensure stable yields. Changing climatic conditions, including rising temperatures and fluctuations in precipitation, require a comprehensive adaptation of agricultural practices, encompassing the optimisation of cultivation techniques and the selection of crops resilient to emerging climatic challenges. Harvests were assessed using a complete (whole-plot) method. The cut grass was weighed immediately, and a representative sample of 1-2 kg was taken for drying. Each sample was labelled with the experiment name, replicate, treatment variant, and date of assessment. The air-dry mass was weighed twice at intervals of 2-3 days, and the lower value was recorded in the log. From this, the hay yield per plot and hectare was calculated. The initial moisture content was determined using the formula:

$$X_1 = \frac{B-C}{B_1} \cdot 100, \tag{1}$$

where B_1 is the sample mass before drying and C is the mass after drying.

The air-dry matter content of the grass was calculated as:

$$100 - X_1. \tag{2}$$

Hay and pasture yields were expressed in terms of absolute dry matter. For this, the hygroscopic moisture in the air-dry mass was determined, after which the total water content in the grass was calculated. To determine hygroscopic moisture, the air-dry mass was chopped, placed in crucibles, weighed, and dried in a thermostat at 100°C-150°C for 4-5 hours. The crucibles with the samples were then removed, placed in a desiccator for one hour to cool, weighed, and the percentage of hygroscopic moisture was calculated using the formula:

$$X_2 = \frac{B_1}{B_2} \cdot 100, \tag{3}$$

where B_1 is the mass after drying (g) and B_2 is the mass of the air-dry sample (g).

The total water content in the grass consists of the initial moisture (X_1) and the hygroscopic moisture (X_2):

$$A = X_1 + \frac{X_2 \cdot (100 - X_1)}{100}. \tag{4}$$

The percentage of absolute dry matter is then 100 − A (%). For the determination of absolute dry matter during harvest assessment, samples of green mass were taken, chopped, placed in crucibles (3-4 per sample), weighed, and dried at 105°C to constant mass according to DSTU ISO 6497:2005 (2008). Botanical composition of the hay was assessed by sorting samples of grass taken for drying from two non-adjacent replicates following DSTU 6017:2008 (2010). Onekilogram portions of grass were divided into three groups: grasses, legumes, and mixed herbs, indicating the predominant species in each group. During species analysis, each sample was separated into individual plant species. The identified species were weighed on laboratory scales with 0.1 g precision, recorded in a botanical analysis register, and calculated as a percentage of the sample mass. Statistical analysis was applied to summarise and process the results of the study (Ushkarenko *et al.,* 2014). The values obtained from the analysis were expressed as percentages, rounded to the nearest whole number for each defined category. The reliability of the analysis was assessed by comparing the extreme values of the replicates with the arithmetic mean.

The energy assessment of the studied practices was carried out in accordance with relevant methodological guidelines and the methodology of O. Medvedovskyi & P. Ivanenko (1988). The study compared energy expenditures for cultivating different types of grass mixtures, considering each stage of the technological process (soil preparation, sowing, fertilisation, harvest, etc.), standardised to a single unit (GJ), and used to determine the active component of each element. Energy analysis of crop production concludes with the calculation of the energy cost of the harvest – the ratio of the amount of non-renewable energy contained in the harvested product to the amount of non-renewable energy expended to produce it. This ratio is referred to as the energy efficiency ratio (EER). During the study, the authors adhered to the norms established by the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Based on the research conducted from 2021 to 2024, the highest yields were observed in multi-component grass mixtures (Table 1).

Table 1. *Grass mixture yields depending on component composition, dry matter t/ha (2021-2024)*

No. Var.	Grass mixture (species)	2021	2022	2023	2024	Average
1	Timothy	7.56	4.44	7.12	5.42	6.14
2	Timothy + Red clover	12.0	10.2	8.24	7.11	9.39
3	Timothy + Alfalfa	7.31	10.0	8.97	6.79	8.27
4	Timothy + Common bird's-foot trefoil	8.66	7.5	8.36	7.98	8.13
5	Timothy + Red clover + Alfalfa + Common bird's-foot trefoil	11.4	10.8	11.4	6.94	10.14
6	Timothy + Perennial ryegrass + Tall fescue + Red clover + Alfalfa + Common bird'sfoot trefoil	12.6	11.8	14.49	7.49	11.60

Source: *developed by the authors*

The highest yield was recorded in variant 6 (timothy, tall fescue, perennial ryegrass, common bird's-foot trefoil, red clover, and alfalfa), which reached 11.60 t/ha. The second most productive mixture consisted of timothy, red clover, common bird's-foot trefoil, and alfalfa, yielding 10.14 t/ha. In variant 2, the mixture including red clover showed a substantial increase in yield (9.39 t/ha) compared with timothy alone (6.14 t/ha). It is worth noting that in the first year, the mixture of timothy and alfalfa produced slightly lower yields than the other variants, reaching 7.31 t/ha of dry matter. The grass mixture of red clover and timothy achieved the highest dry-matter yield among two-component mixtures, at 9.39 t/ha.

The data indicate that in the first year of use, the rate of vegetative mass accumulation in red clover was considerably higher than in common bird's-foot trefoil or alfalfa. The accumulation of green mass in alfalfa was significantly lower compared with common bird's-foot trefoil. However, by the second year, this figure increased to 10.0 t/ha. As shown in the table, the yield of timothy in 2021 was 7.56 t/ha, but it declined to 4.44 t/ha the following year. Botanical analysis indicates changes in the proportion of different plant groups in the harvest structure across the three cuttings (Table 2). Grasses generally dominate the first cutting, comprising around 86% of the yield; however, their share decreases in subsequent cuttings, while the proportion of herbs increases, reflecting the depletion of grasses and the growth of competing species. The inclusion of leguminous plants (red clover, common bird's-foot trefoil, alfalfa) significantly reduces the proportion of grasses in the green mass yield.

Table 2. *Botanical composition of sown stands depending on the species composition of the mixtures,% of green mass (average 2021-2024)*

No. Var.	Grass mixture (species)	Plant type	Cutting I	Cutting II	Cutting III
1	Timothy	Grasses	86	75	84
		Herbs	14	25	16

Table 2. Continued

No. Var.	Grass mixture (species)	Plant type	Cutting I	Cutting II	Cutting III
2	Timothy + Red clover	Grasses	51	81	45
		Legumes	45	10	48
		Herbs	5	15	7
3	Timothy + Alfalfa	Grasses	42	40	21
		Legumes	52	54	74
		Herbs	7	7	4
4	Timothy + Common bird's-foot trefoil	Grasses	43	45	37
		Legumes	49	48	55
		Herbs	8	7	8
5	Timothy + Red clover + Alfalfa + Common bird's-foot trefoil	Grasses	32	46	23
		Red clover	46	3	27
		Alfalfa	22	34	38
		Common bird's-foot trefoil	8	13	8
		Herbs	4	7	5
6	Timothy + Perennial ryegrass + Tall fescue + Red clover + Alfalfa + Common bird's-foot trefoil	Grasses	34	46	26
		Red clover	43	3	37
		Alfalfa	23	30	26
		Common bird'sfoot trefoil	6	14	7
		Herbs	6	10	4

Source: *developed by the authors*

In variant 2 (timothy + red clover), the proportion of grasses decreases to 51%, while legumes account for 45%. In the variant sown with alfalfa and timothy, the legume content reaches 52%-74%, particularly in the third cutting, indicating a gradual increase in their productivity. Variant 4 (timothy + common bird's-foot trefoil) demonstrates a more balanced composition, with a relatively even proportion of grasses (37%-45%) and legumes (48%-55%), indicating a stable growth dynamic between both plant groups. According to research, increasing diversity in grass mixtures promotes more even resource utilisation and enhances grass stand stability. The variant including timothy, red clover, alfalfa, and common bird's-foot trefoil exhibited the greatest variability in species proportions: red clover (3%-46%), alfalfa (22%-38%), and common bird'sfoot trefoil (8%-13%), allowing a gradual increase in their share over successive cuttings. The multicomponent mixture (Variant 6) was characterised by a balanced ratio of grasses (26%-46%), red clover (3%-43%), alfalfa (23%-30%), and common bird's-foot trefoil (6%-14%), reflecting a more even coexistence of different species, which positively influences grass stand resilience.

Overall, increasing the proportion of legumes in grass mixtures improves total yield, particularly in later cuttings. Multi-component mixtures are more stable in terms of productivity, as different plant species compensate for seasonal fluctuations in each other's growth. In contrast, dominance of grasses is observed in single- or low-component mixtures, whereas in complex mixtures the share of grasses gradually declines. The study also found that energy expenditure for soil preparation and harvest constitutes a significant portion of total energy costs for crop production. Therefore, reducing energy inputs at these stages could substantially enhance the energy efficiency of the cultivation technology. The botanical composition of grass mixtures directly affects their energy efficiency, that is, the ratio of energy invested to energy obtained from the harvest. Analysis of the data indicates that mixed stands containing both grasses and legumes are more productive and energy-efficient (Table 3).

Table 3*. Energy efficiency of sown stands depending on the species composition of grass mixtures (2021-2024)*

No. Var.	Grass mixture (species)	Energy expenditure for crop cultivation, GJ	Gross energy output from the harvest, GJ	Metabolisable energy output, GJ	EER
1	Timothy	19.4	103.1	59.2	3.0
2	Timothy + Red clover	22.4	164.3	94.3	4.2
3	Timothy + Alfalfa	22.6	142.0	81.5	3.6
4	Timothy + Common bird's-foot trefoil	22.4	132.3	75.9	3.4
5	Timothy + Red clover + Alfalfa + Common bird's-foot trefoil	25.9	181.3	104.1	4.0
6	Timothy + Perennial ryegrass + Tall fescue + Red clover + Alfalfa + Common bird's-foot trefoil	28.7	209.7	120.4	4.2

Source: *developed by the authors*

Energy expenditure for cultivating grass mixtures varies according to their composition. The lowest energy input (19.4 GJ) was observed for pure timothy, reflecting its low maintenance requirements. In two-component mixtures (timothy + red clover or alfalfa), energy expenditure rises to 22.4-22.6 GJ due to the higher maintenance demands of legumes. The highest energy input (28.7 GJ) was recorded for the multi-component mixture (Variant 6), where grasses (timothy, perennial ryegrass, tall fescue) are grown together with several legume species (red clover, alfalfa, common bird's-foot trefoil). The greater the diversity of the grass mixture, the higher the gross energy output. A monoculture of timothy yields 103.1 GJ, whereas the six-species mixture produces 209.7 GJ. A pure stand of timothy provides 59.2 GJ of metabolisable energy; when red clover or alfalfa is added, this rises to 75.9-94.3 GJ. The highest metabolisable energy (120.4 GJ) was observed in the multi-component mixture (Variant 6), making it the most nutritious and energy-efficient as fodder.

The lowest EER of 3.0 was recorded for pure timothy, indicating that its cultivation is less advantageous from an energy perspective. The highest EER of 4.2 was observed in two mixtures: (timothy + red clover) and (timothy + red clover + perennial ryegrass + tall fescue + red clover + common bird's-foot trefoil + alfalfa), reflecting a high energy return and making these mixtures optimal for cultivation. Thus, mixed grass–legume mixtures provide a higher energy yield, enhancing their feed value. Multi-component mixtures (Variants 5 and 6) demonstrated the highest metabolisable energy output and efficiency ratio, making them the most favourable for cultivation. The inclusion of legumes (red clover, alfalfa, common bird's-foot trefoil) improves the energy balance of the sward, reducing dependence on additional fertilisation.

According to O. Rognli *et al.* (2021), legume-grass stands provide high-quality fodder with lower energy and financial inputs due to the high productivity of these stands. They can increase yields by 1.3-2.0 times without the application of nitrogen fertilisers compared with grass-only stands, thereby reducing nitrogen requirements and improving overall soil fertility. Legume-grass stands surpass other fodder types in protein, mineral, and vitamin content, with a single feed unit containing 140-160 g of digestible protein, compared with only 62-95 g in cereal grains. The careful selection of fodder species in optimal proportions enhances the productivity of grasslands. It also allows for the production of balanced plant material in terms of nutrients while reducing production costs. In stands, legumes should exhibit high vigour and productivity, while grasses are expected to form a strong root system. Phenological studies confirm that grasses vary in growth and development rates, being classified as early-, mid-, or late-maturing. This classification enables a continuous supply of green fodder, extending the harvesting period without compromising feed quality (from 7 up to 25-38 days). Morphological and agronomic traits of different grass and legume species are determined by root system types, which differ in branching and depth of soil penetration during the growing season, ensuring efficient uptake of nutrients from various soil layers.

Red clover is most commonly sown in a mixture with common bird's-foot trefoil, as the latter compensates for any losses of clover in the stand. Common bird's-foot trefoil is a perennial plant that can persist in the stand for 6-8 years. I. Senyk (2020) and V. Olifirovych & Yu. Veklenko (2021) noted that common bird's-foot trefoil can be successfully cultivated even on low-fertility and acidic soils, where other legumes perform poorly. In addition, common bird's-foot trefoil is frost-tolerant and exhibits greater resistance to pests and diseases compared with other legume species. According to K. Kovtun *et al.* (2020), it has high nutritional and fodder value; its hay contains 14%-22.3% protein, 1.5%-3.6% fat, 22.4%-26.0% fibre, 39%-51% digestible nutrients, and 6.9%-11.2% ash. The stand tolerates regular mowing and grazing well. All researchers emphasise the importance of studying the development of legume-grass mixtures under changing climatic conditions. These findings should be considered when designing grass mixtures for hay production, as they contribute to higher yields and improved feed quality.

CONCLUSIONS

Research showed that multi-component grass mixtures yield more and are more stable compared with single- or low-component mixtures. The best results were obtained from a mixture comprising timothy, tall fescue, perennial ryegrass, red clover, alfalfa, and common bird's-foot trefoil, with an average yield of 11.60 t/ha. The high efficiency of these mixtures is attributed to the ability of different species to compensate for each other's seasonal growth fluctuations and to provide a balanced proportion of grasses and legumes. A stand of timothy and legume species (red clover, common bird's-foot trefoil, and alfalfa) also performed well, ranking second in productivity. The lowest average yield was observed in the treatment with timothy as the sole component (6.13 t/ha). Therefore, for a stable yield, it is advisable to use multi-component mixtures that combine grasses and legumes.

The inclusion of legumes in the grass mixtures composition significantly alters the harvest structure: the proportion of grasses decreased from 86% in the timothy monoculture to 21%-45% in mixed stands, while legumes accounted for 48%-74%, particularly in the later cuttings. The most stable results were observed in the multi-component mixtures (variants 5 and 6), where grasses comprised 26%-46% and legumes up to 74%, ensuring uniform growth, high adaptability, and stable productivity of the sown agrocenoses in the Precarpathian region. Future research should focus on the detailed study of legume persistence in perennial cenoses, the development of adaptive fertilisation schemes for different mixture types, and the assessment of how agronomic practices influence feed quality and the ecological stability of sown areas in the Foothill zone. Hence, a multi-component grass mixture represents an optimal choice for cultivation, as it provides the highest energy yield with relatively moderate inputs.

ACKNOWLEDGEMENTS

None.

FUNDING

This study was conducted under the commission of the National Academy of Agrarian Sciences of Ukraine in accordance with task 09.01.04.02.F, "Improving the scientific foundations for modelling meadow phytocoenoses of multifunctional use within zonal adaptive-landscape systems for meadow forage production in the Precarpathian region".

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

REFERENCES

[1] Babych, A.O., Kulyk, M.F., & Makarenko, P.S. (1998). *Methodology for conducting experiments on feed production and animal feeding*. Kyiv: Ahrarna Nauka.

[2] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.

[3] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1979, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.

[4] de Haas, B., Hoekstra, N., Schoot, J.R., Visser, E.J., Kroon, H., & Eekeren, N.V. (2019). Combining agro-ecological functions in grass-clover mixtures. *AIMS Agriculture and Food*, 4(3), 547-567. doi: 10.3934/agrfood.2019.3.547.

[5] DSTU 6017:2008. (2010). *Natural fodder grounds. The method of botanical research of the grass stands*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=91707.

[6] DSTU ISO 6497:2005. (2008). *Fodder for animals. Sampling methods (ISO 6497:2002, IDT)*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=91972.

[7] Dziubailo, A.H., & Pylypiv, N.I. (2022). The dynamics of the sowed herb density depending on the fertilization. *Foothill and Mountain Agriculture and Animal Husbandry*, 71(1), 80-95. doi: 10.32636/01308521.2022-(71)-1-5.

[8] Feng, Y., *et al*. (2022). Yield and quality properties of alfalfa (*Medicago sativa* L.) and their influencing factors in China. *European Journal of Agronomy*, 141, article number 126637. doi: 10.1016/j.eja.2022.126637.

[9] Karbivska, U.M., Martyshchuk, V., Kyrhak, V., & Voloshchuk, M. (2020). Effectiveness of the surface improvement of the mountain slope meadows of the Carpathians. *Bulletin of Agrarian Science*, 98(7), 38-45. doi: 10.31073/agrovisnyk202007-05.

[10] Komainda, M., Küchenmeister, K., Küchenmeister, F., Breitsameter, L., Wrage-Mönnig, N., Kayser, M., & Isselstein, J. (2019). Forage legumes for future dry climates: Lower relative biomass losses of minor forage legumes compared to Trifolium repens under conditions of periodic drought stress. *Journal of Agronomy and Crop Science*, 205(5), 460-469. doi: 10.1111/jac.12337.

[11] Kovtun, K.P., Veklenko, Yu.A., Korniichuk, O.V., & Babych-Poberezhna, A.A. (2020). Biochemical composition and forage productivity of lotus corniculatus (*Lotus Corniculatus* L.) in the conditions of the Right Bank Forest Steppe of Ukraine. *Norwegian Journal of Development of the International Science*, 2(45), 4-7.

[12] Kurhak, V.H., & Karbivska, U.M. (2020). Features of the formation of legume-cereal agrophytocenoses on sod-podzolic soils of the Carpathian region of Ukraine. *Feeds and Feed Production,* 89, 121-133. doi: 10.31073/kormovyrobnytstvo202089-12.

[13] Martsinko, T.I. (2020). The influence of fertilizer on the productivity and botanical and economic composition of sown meadow agrocenoses. *Foothill and Mountain Agriculture and Animal Husbandry,* 68(1), 135-145. doi: 10.32636/01308521.2020-(68)-1-10.

[14] Medvedovskyi, O.K., & Ivanenko, P.I. (1988). *Energy analysis of intensive technologies in agricultural production*. Kyiv: Urozhay.

[15] Monjardino, M., Loi, A., Thomas, D.T., Revell, C.K., Flohr, B.M., Llewellyn, R.S., & Norman, H.C. (2022). Improved legume pastures increase economic value, resilience and sustainability of crop-livestock systems. *Agricultural Systems*, 203, article number 103519. doi: 10.1016/j.agsy.2022.103519.

[16] Olifirovych, V.O., & Veklenko, Yu.A. (2021). Increasing the efficiency of cultivation of alfalfa and cereal grass mixtures on eroded slopes. *Feeds and Feed Production*, 91, 93-102. doi: 10.31073/kormovyrobnytstvo202191-08.

[17] Panakhyd, H., Konyk, H., & Stasiv, O. (2020). Economic evaluation of models ofestablishmentand use technologies of legume-grass. *Agricultural and Resource Economics: International Scientific E-Journal,* 6(3), 221-234. doi: 10.51599/are.2020.06.03.12.

[18] Patra, P.S., & Paul, T. (2021). Lucerne (Alfalfa). In Md. Hedayetullah & P. Zaman (Eds.), *Forage crops of the world* (pp. 231-243). Florida: CRC Press, Apple Academic Press, Inc.

[19] Petrychenko, V.F., Hetman, N.Ia., & Veklenko, Yu.A. (2020). The rationale for the productivity of seeded alfalfa under long-term use of grass stands under climate change conditions. *Bulletin of Agrarian Science*, 98(3), 20-26. doi: 10.31073/agrovisnyk202003-03.

[20] Rognli, O.A., Pecetti, L., Rao Kovi, M., & Annicchiarico, P. (2021). Grass and legume breeding match the future needs of European grassland farming. *Grass and Forage Science*, 76(2), 175-185. doi: 10.1111/gfs.12535.

[21] Senyk, I.I. (2020). The formation of the botanical composition of clover-cereal and alfalfa-cereal agrophytocenoses depends on the sowing method. *Agrobiology,* 1, 160-169. doi: 10.33245/2310-9270-2020-157-1-160-168.

[22] State register of plant varieties suitable for distribution in Ukraine. (2025). Retrieved from https://minagro.gov.ua/napryamki/roslinnictvo/reyestr-sortiv-roslin-ukrayini/reyestr-sortiv-roslin-ukrayini.

[23] Ushkarenko, V.O., Vozhehova, R.A., Holoborodko, S.P., & Kokovikhin, S.V. (2014). *Methodology of the field experiment*. Kherson: D.S. Grin.

[24] Zhang, H.H., Shi, S.L., Wu, B., Li, Z.L., & Li, X.L. (2022). A study of yield interactions in mixed sowings of alfalfa and three perennial grasses. *Acta Prataculturae Sinica*, 31(2), 159-170. doi: 10.11686/cyxb2021175.

[25] Zhang, Y.L., Teng, Z., Hao., Yu, T.F., & Zhang, Y.X. (2024). Effects of different mixed sowing patterns and sowing ratios of alfalfa on grassland productivity and community stability in grass-legume mixtures. *Acta Prataculturae Sinica*, 33(2), 185-197. doi: 10.11686/cyxb2023161.

Оцінка впливу компонентного складу травосумішей на продуктивність сіяних агроценозів в умовах Передкарпаття

Наталія Карасевич

Доктор філософії, старший науковий співробітник
Інститут сільського господарства Карпатського регіону Національної академії аграрних наук
81115, вул. Грушевського, 5, с. Оброшине, Україна
https://orcid.org/0000-0002-1416-559X

Тарас Марцінко

Кандидат сільськогосподарських наук, провідний науковий співробітник
Інститут сільського господарства Карпатського регіону Національної академії аграрних наук
81115, вул. Грушевського, 5, с. Оброшине, Україна
https://orcid.org/0000-0002-6912-420X

Любомир Бугрин

Кандидат сільськогосподарських наук, старший науковий співробітник
Інститут сільського господарства Карпатського регіону Національної академії аграрних наук
81115, вул. Грушевського, 5, с. Оброшине, Україна
https://orcid.org/0000-0001-6180-203X

Андрій Дзюбайло

Доктор сільськогосподарських наук, головний науковий співробітник
Інститут сільського господарства Карпатського регіону Національної академії аграрних наук
81115, вул. Грушевського, 5, с. Оброшине, Україна
https://orcid.org/0000-0002-1309-6924

Степан Бегей

Кандидат сільськогосподарських наук, провідний науковий співробітник
Інститут сільського господарства Карпатського регіону Національної академії аграрних наук
81115, вул. Грушевського, 5, с. Оброшине, Україна
https://orcid.org/0000-0002-7193-0550

Анотація. Метою дослідження було встановити вплив компонентного складу багаторічних травосумішей на продуктивність сіяних агроценозів у ґрунтово-кліматичних умовах Передкарпаття. Польові дослідження проводили у 2020-2024 роках на дерново-підзолистих ґрунтах із використанням безпокривного літнього способу сівби та застосуванням мінерального удобрення в дозі $N_{30}P_{60}K_{90}$ відповідно до методичних рекомендацій Національної академії аграрних найк України. Урожайність оцінювали поділяночно-ваговим методом; вміст абсолютно сухої речовини визначали шляхом висушування зразків при температурі 105 °C; ботанічний склад травостоїв аналізували на основі вибіркових проб зеленої маси. Результати досліджень засвідчили, що найбільшу продуктивність забезпечували багатокомпонентні травосуміші, до складу яких входили як злакові, так і бобові види. Встановлено позитивний вплив оптимального співвідношення компонентів у сумішах на показники урожайності сухої речовини, енергетичну ефективність та стійкість травостоїв. Узагальнення результатів показало, що включення бобових культур, зокрема конюшини лучної (*Trifolium pratense*), люцерни посівної (*Medicago sativa*) та лядвенцю рогатого (*Lotus corniculatus*), сприяло підвищенню урожайності на 30-45 % порівняно з одновидовими посівами. Проаналізовано динаміку зміни ботанічного складу протягом трьох укосів. Встановлено, що багатокомпонентні травосуміші формують стабільнішу структуру травостоїв і забезпечують вищу частку бобових компонентів у другому та третьому укосах. Проведена енергетична оцінка підтвердила доцільність використання змішаних посівів завдяки вищому коефіцієнту енергетичної віддачі. Отримані результати можуть бути використані агрономами, фахівцями з кормовиробництва та екосистемного землеробства для створення високопродуктивних і стабільних травостоїв у зоні Передкарпаття

Ключові слова: продуктивність урожаю; вміст сухої речовини; ботанічний склад травостою; травосуміші; енергетична ефективність

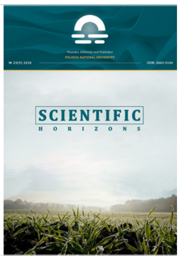
ISSN 2663-2144 e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 29(1), 20-29

UDC 633.34:631.811:632.9 DOI: 10.48077/scihor1.2026.20



Formation of soybean seed quality depending on plant protection in the forest-steppe of Ukraine

Vitalii Kravchenko
PhD in Agricultural Sciences, Associate Professor
Uman National University of Horticulture
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-4873-5367

Yurii Novak
PhD in Agricultural Sciences, Associate Professor
Uman National University of Horticulture
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-2042-521X

Lesia Vyshnevska
PhD in Agricultural Sciences, Associate Professor
Uman National University of Horticulture
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0001-9470-9050

Serhii Rohalskyi
PhD in Agricultural Sciences, Associate Professor
Uman National University of Horticulture
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0009-0007-5739-8717

Andrii Sichkar
PhD in Agricultural Sciences, Associate Professor
Uman National University of Horticulture
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0009-0005-0169-8839

Article's History:
Received: 01.10.2025
Revised: 03.03.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. The aim of the study was to establish the patterns of formation of soybean seed productivity and quality depending on weather conditions and varietal characteristics in the Right-Bank Forest-Steppe of Ukraine. Field studies were conducted during 2023-2025 on experimental plots in the Uman district of the Cherkasy region. The object of the research was five soybean varieties of different genetic origin and morphobiological characteristics: Gallek, ES Mentor, OAC Brook, Sigalia, and Kobza. The soil and climatic conditions during the years of research differed significantly in terms of temperature and moisture supply, which made it possible to assess the adaptive potential of varieties under contrasting hydrothermal conditions. Methodologically, the research was based on a field experiment taking into account the main elements of the yield structure, the

Suggested Citation:
Kravchenko, V., Novak, Yu., Vyshnevska, L., Rohalskyi, S., & Sichkar, A. (2026). Formation of soybean seed quality depending on plant protection in the forest-steppe of Ukraine. *Scientific Horizons*, 29(1), 20-29. doi: 10.48077/scihor1.2026.20.

**Corresponding author*

weight of 1,000 seeds, the fractional composition of the seeds and quality indicators. The protein and oil content in the seeds was determined by infrared spectroscopy, and the moisture content was determined by a standard laboratory method. The dynamics of above-ground biomass formation were analysed using the sum of effective temperatures and a logistic growth model. It was found that in 2024, under conditions of moisture deficiency and elevated temperatures, the rate of biomass growth, 1,000-seed weight, and yield decreased by 8-25% compared to 2023 and 2025. According to the average three-year data, the highest and most stable yields were formed by the ES Mentor and Kobza varieties, while the Gallek and Sigalia varieties were more sensitive to stressful conditions. Seed quality indicators were mainly determined by variety: the Gallek variety was distinguished by the highest weight of 1,000 seeds and a high proportion of large seeds, while the protein and oil content remained relatively stable throughout the years of research. The practical value of the work lies in substantiating the feasibility of selecting soybean varieties with high ecological plasticity and stable seed quality for the conditions of the Right-Bank Forest-Steppe of Ukraine in the context of increasing climate variability

Keywords: soybean productivity; varietal characteristics; seed quality; sugar content; economic efficiency; inoculation; cultivation technology

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the strategically important leguminous crops in global agriculture due to its high nutritional value, significant protein and oil content, and wide range of uses in the food, feed and processing industries. Soybeans play an increasingly important role in the structure of agricultural production in Ukraine, as they combine high economic potential with the ability to adapt to different soil and climatic conditions. At the same time, modern challenges related to climate change, soil degradation and the need to improve resource efficiency necessitate the improvement of crop cultivation technologies and the optimisation of agrotechnical elements. An important component of stable soybean production is the selection of varieties capable of ensuring high yields and seed quality in changing agroecological conditions. According to the results of research by M. Alburaki *et al.* (2024), varietal characteristics significantly affect crop productivity, its adaptability to abiotic factors, and the realisation of yield potential. Similar conclusions were reached by Z.I. Hlupak (2020), who found that the varietal response of soybeans to moisture and temperature conditions is a determining factor in yield formation in different agroclimatic zones.

The problem of soybean variety adaptability to changing environmental conditions is also highlighted in the works of O. Laslo *et al.* (2024), which emphasise the significant variability of productivity indicators depending on the combination of genetic characteristics of the variety and growing conditions. The authors emphasise that the potential of modern varieties can only be realised with an optimal combination of agronomic factors. Similar conclusions were reached by L. Bilavska & A. Rybalchenko (2019), who point to significant differences between varieties in terms of protein content and other economically valuable traits, caused by both genetic and environmental factors. The mineral nutrition system has a significant impact on the formation of the yield and quality indicators of seeds. M. Ivasyk & M. Bakhmat (2022) proved that balanced fertilisation contributes to increased yield and improved grain quality, but the effectiveness of such measures largely depends on soil and climatic conditions and the biological characteristics of the variety.

The impact of plant protection systems on crop formation and seed quality characteristics is of particular scientific interest. S.P. Hen *et al.* (2022) showed that the use of modern protection schemes can reduce crop losses from phytopathogens and stabilise productivity indicators, while the intensity of chemical load can affect the physiological state of plants. Climatic factors also make a significant contribution to the formation of soybean quality indicators. A. Riabultchenko & A. Serdiuk (2023) emphasised the complex nature of the relationship between yield, protein content and oil content of seeds depending on weather conditions during the growing season. A review of current scientific sources has shown that the formation of soybean seed quality indicators is a multifactorial process determined by a combination of genetically determined characteristics of the variety, agrotechnical features, plant protection systems, and specific soil and climatic conditions of cultivation. Despite the availability of a significant number of scientific works devoted to individual elements of soybean cultivation technology, there is a lack of systematic research in the scientific community aimed at a comprehensive assessment of the interaction between varietal characteristics and elements of the plant protection system in the formation of sowing and quality indicators of seeds. Generalised data on such interactions in the soil and climatic conditions of the Right-Bank Forest-Steppe of Ukraine, which are characterised by increased variability of weather factors and specific agro-ecological conditions, remain particularly limited. In this regard, there is a need for an in-depth scientific analysis of the role of varietal characteristics and technological elements in the formation of soybean seed quality, taking into account regional specifics, which determines the relevance of conducting relevant research and determines its scientific and practical significance. That is why the aim of the study was to determine the influence of varietal characteristics and elements of the plant protection system on the formation of sowing and quality indicators of soybean seeds in the conditions of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

Research on the productivity and quality of soybean seeds depending on varietal characteristics, plant protection systems, and foliar fertilisation was conducted in 2023-2025 on the experimental field of the Department of Plant Growing of Uman National University (Cherkasy region), which belongs to the Right-Bank Forest-Steppe zone of Ukraine. The soil of the experimental site is podzolised medium loam chernozem with a humus content of 3.4-4.1% and a pH of 6.4-6.7. The climate of the region is temperate continental with an average annual precipitation of 520-580 mm. Weather conditions during the years of research differed significantly in terms of temperature and moisture supply, creating a contrasting background for assessing varietal responses. The meteorological conditions during the years of the study were characterised by significant variability in temperature and precipitation, which made it possible to evaluate the response of soybean plants to different levels of heat and moisture supply (Central Geophysical Observatory named after Borys Sreznevskyi, 2024). To quantitatively assess heat resources, was used the Growing Degree Days (GDD) index, which was calculated using the formula:

$$\mathrm{GDD} = \Sigma(T_{ser} - T_o), \tag{1}$$

where T_{ser} – average daily air temperature, °C; T_o – base temperature for soybean growth, assumed to be 10°C.

To analyse the dynamics of above-ground biomass growth, a logistic growth model was used, which is described by the equation:

$$Y = Y_{asym}/(1 + \mathrm{e}^{-k}(\mathrm{GDD} - t_m)), \tag{2}$$

where Y – accumulated above-ground biomass; Y_{asym} – asymptotic (maximum) biomass value; k – growth intensity coefficient; t_m – GDD value at the inflection point of the growth curve.

The model parameters were estimated using nonlinear regression. The quality of the approximation was checked using the coefficient of determination (R^2) and the root mean square error. Field experiments were conducted using a three-factor design (variety × protection system × foliar feeding) in four replicates: factor A – variety: ES Mentor, Gallek, OAC Brook, Sigalia, Kobza; factor B – plant protection system: control (without treatment), chemical, biological, integrated; factor C – foliar feeding: growth regulator Rizohumin-Plus in concentrations of 0.5% and 0.75%. Sowing was carried out with a row spacing of 70 cm and a sowing rate of 450 thousand viable seeds/ha. Application phases and application rate: foliar feeding with chlormequat chloride Rizohumin-Plus was performed twice:

- in the phase of the 3rd-5th true leaf (V3-V5) and in the phase of budding (R1), working solution rate – 400 l/ha;
- for the plant protection system (chemical, biological, integrated), the preparations recommended for soybeans were used, according to the phases: weed control – before emergence; fungicide and insecticide – in the V4-V6 phase; working solution consumption rate – 300-400 l/ha, frequency – 1-2 times depending on the type of protection.

During the growing season, phenological observations, biometric measurements (plant height, number of nodes, pods, grains per pod, weight of 1,000 seeds), assessment of plant density and activity of symbiotic structures were carried out. Seed quality was assessed based on a set of indicators:

- fractional composition: calibration through 7.0, 6.0, and 5.0 mm sieves;
- weight of 1,000 seeds: triple weighing (DSTU 4138-2002, 2004);
- moisture content determined by standard method;
- protein and oil content: infrared spectroscopy (NIR, DSTU EN ISO 12099:2022, 2023);
- total sugars and sucrose: extraction-chromatographic method;
- symbiotic efficiency of soybeans was assessed by the weight of nodules in phases R3-R6 and calculated indicators of active symbiotic potential and biologically fixed nitrogen, averaged for 2023-2025. The mass of biologically fixed nitrogen was calculated based on the symbiotic potential value, converted per plant and per hectare.

Statistical data processing was performed with the determination of $\mathrm{LSD}_{0.5}$. To assess the impact of factors, dispersion analysis was used, statistical significance was determined at $p < 0.05$, and the average values were compared using standard statistical methods. Correlation analysis was used to determine the relationship between seed weight, protein content and other quality indicators. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Weather conditions during the years of research differed significantly in terms of temperature and moisture supply, which created a contrasting background for assessing the response of soybean plants. The lowest amount of precipitation during the growing season was observed in 2024 (166.0 mm), while in 2025 it reached

359.8 mm. At the same time, 2024 was characterised by the highest number of days with air temperatures above +35°C, which created stressful conditions for plant growth (Table 1).

***Table 1**. Weather conditions and soybean growth parameters in the Right-Bank Forest-Steppe of Ukraine (2023-2025)*

Indicator	2023-2024	2024-2025	$LSD_{0.5}$
Precipitation during the growing season (May-October), mm (V-X)	166.0	359.8	18
Annual precipitation, mm	487.2	525.5	27
Average annual air temperature, °C	11.8	10.3	0.4
Average temperature during the growing season (V-VIII), °C	20.1	18.6	0.3
Number of days with temperatures > +35 °C	25	10	2
Biomass growth rate, k (GDD^{-1})	5.80×10^{-3}	6.72×10^{-3}	0.13×10^{-3}
Biomass asymptote, Yasym (kg/ha)	6,345	7,015	145
Inflection point tm (GDD)	845	905	22

***Source:** developed by the authors*

The results of growth modelling show that in conditions of moisture deficiency and elevated temperatures, the rate of biomass accumulation decreased, as evidenced by lower values of the coefficient k and the asymptotic biomass level (Y_{asym}). In contrast, in years with better hydrothermal conditions, these indicators increased, indicating more active growth processes and more efficient use of thermal resources. Among the varieties studied, the highest average yield for 2023-2025 was provided by ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha), confirming their high plasticity and ability to form a stable yield even under contrasting weather conditions. The years of research differed significantly in terms of hydrothermal conditions: during the growing season, precipitation ranged from 42.4-15.8 – -92.5 mm (2023) to 15.4-99.2-10.0 mm (2025), which caused fluctuations in moisture availability at certain stages of plant growth. A particularly acute precipitation deficit was observed in 2024, while 2023 was characterised by a more even distribution. In addition to yield, an important indicator of the technological value of varieties is the fractional composition of seeds, as it determines the suitability of the crop for processing and seed production. The weight of 1,000 seeds, the proportion of large seeds, and seed uniformity are key criteria that are determined by a combination of factors, including the biology of the variety, moisture availability, and temperature conditions. According to the results of the research, the largest proportion of the large fraction was formed by the varieties Gallek, ES Mentor and OAC Brook, which confirms their better response to the moderate moisture conditions of 2023 and 2025 (Table 2).

***Table 2**. Fractional composition of soybean seed depending on the variety, average for 2023-2025, %*

Variety	Large fraction (>5.0 mm)	Medium (4.0-5.0 mm)	Small (<4.0 mm)
Gallek	63.5	31.8	4.7
ES Mentor	59.2	36.1	4.7
OAC Brook	50.4	47.3	2.3
Sigalia	44.6	37.9	17.5
Kobza	47.2	44.4	8.4
LSD $_{(p<0.05)}$	4.55	4.10	3.35

***Source:** developed by the authors*

During 2023-2025, it was established that the formation of quality indicators for soybean seeds and yields was largely determined by variable weather conditions. In 2023, with moderate rainfall and no prolonged droughts, most varieties produced a higher proportion of large seeds and yielded maximum harvests. In 2024, when there was a moisture deficit during the critical stages of branching and flowering, the yield of most varieties decreased, and the proportion of small seeds increased. The Kobza and ES Mentor varieties performed best under these conditions, maintaining a relatively even fraction composition. In 2025, a sharp contrast in precipitation (excess at the beginning and deficit at the end of the growing season) contributed to an increase in the average fraction and a decrease in the small fraction in varieties with high adaptive potential. ES Mentor and Kobza provided the highest stability of indicators, forming a yield of 3.15-3.41 t/ha.

According to the average results for 2023-2025, the highest yields were provided by: ES Mentor – 3.30 t/ha; Kobza – 3.16 t/ha. The lowest average productivity was observed for Gallek (2.66 t/ha) and Sigalia (2.64 t/ha). Overall, the data demonstrate significant varietal differentiation and make it possible to recommend the most productive and stable varieties for the Forest-Steppe zone of Ukraine. In the dry year of 2024, against the backdrop of high temperatures and moisture deficiency, there was an overall decrease in the weight of 1,000 seeds by 8-10% and a decrease in the large fraction by 5-7%. This directly affected the yield, as its decline ranged from 0.2 to 0.5 t/ha depending on the variety. The smallest decrease was observed in the OAC Brook variety, while Gallek and Sigalia proved to be more sensitive to stressful conditions. In 2025, with more optimal moisture and temperature conditions, most varieties restored their productivity to 2023 levels. ES Mentor and Kobza again showed the highest yield values – from 3.33 to 3.40 t/ha. The Sigalia variety showed moderate but stable performance, ranging from 2.75 to 2.93 t/ha. According to the average results of three-year studies, the highest yields were provided by the ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha) varieties. Slightly lower but more consistent results were obtained for the OAC Brook variety – 3.09 t/ha. The lowest average productivity was achieved by the varieties Gallek (2.66 t/ha) and Sigalia (2.64 t/ha). In general, the data obtained demonstrate significant varietal differentiation in terms of productivity and allow for the recommendation of the most productive and stable varieties for cultivation in the forest-steppe zone of Ukraine (Table 3).

***Table 3**. Weight of 1,000 seeds and protein content in soybean varieties in the Uman district of the Cherkasy region*

Variety	Weight of 1,000 seeds, g (±σ)	CV% of weight	Protein content, % (±σ)	CV% of protein
Gallek	160 ± 3.0	1.9	34.2 ± 0.6	1.8
ES Mentor	156 ± 3.0	1.9	33.5 ± 0.6	1.8
OAC Brook	152 ± 3.0	2.0	32.5 ± 0.6	1.8
Sigalia	146 ± 3.0	2.1	32.0 ± 0.6	1.9
Kobza	151 ± 3.0	2.0	33.8 ± 0.6	1.8
LSD $_{(p<0.05)}$	6.74	–	1.8	–

***Source:** developed by the authors*

The graph shows the ratio of seed weight to protein content, allowing for a visual assessment of the differences between varieties in terms of these indicators (Fig. 1).

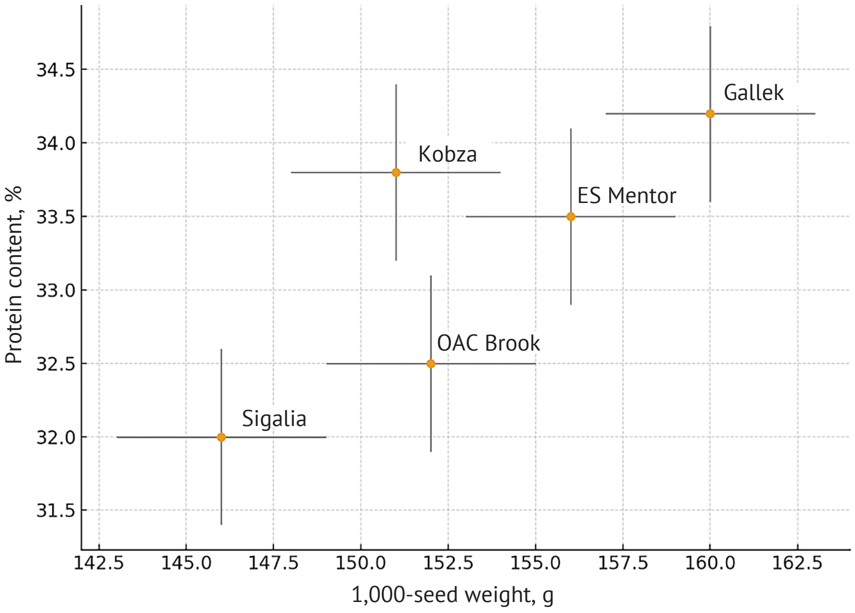


***Figure 1**. Ratio of the weight of 1,000 seeds and protein content in soybean varieties in the Uman district of the Cherkasy region*

***Source:** developed by the authors*

The conducted research confirmed significant variability in the indicators. The highest weight of 1,000 seeds was recorded for Gallek (160 g) and ES Mentor (156 g), while the lowest was recorded for Sigalia (146 g), which was combined with the largest proportion of small fraction (<4 mm – 17.5%). The protein content ranged from 32.0% (Sigalia) to 34.2% (Gallek), indicating the overall stability of this indicator. There was a tendency towards an inverse relationship between seed weight and protein content, confirmed by correlation analysis. The data can be used to select varieties for the conditions of the Central Forest-Steppe of Ukraine. To assess the quality of soybean seeds, it is important to consider not only the yield, but also the chemical composition of the seeds, in particular the protein and oil content, which was determined by near-infrared spectroscopy (NIR), as well as the composition of protein fractions, amino acids and sugars. These indicators determine the food and feed value of the crop, as well as its technological suitability for processing. During the 2023-2025 studies, the content of globulins, albumins, gliadins, lysine and methionine, fat and acid composition of oil, total sugars and sucrose, as well as active symbiotic potential were analysed. The calculation of LSD$_{0.5}$ allows to assess the reliability of differences between varieties (Table 4).

***Table 4**. Protein and oil content, chemical composition and quality of seeds of the studied soybean varieties (average for 2023-2025, determined by near-infrared spectroscopy)*

Variety	Globulins, %	Albumins, %	Gliadins, %	Lysine, %	Methionine, %	Oil, %	Saturated acids, %	Unsaturated acids, %	Total sugars, %	Sucrose, %	Active symbiotic potential, thousand kg·day/ha	Moisture, %
Gallek	70	20	10	6.1	1.2	19.0	16	84	6.2	4.4	22.34	11.2
ES Mentor	68	22	10	6.0	1.2	18.5	16	84	7.8	5.6	16.46	11.5
OAC Brook	67	23	10	5.9	1.1	18.0	16	84	7.5	5.3	15.88	11.3
Sigalia	66	24	10	5.8	1.1	18.2	16	84	6.1	4.3	15.72	11.4
Kobza	69	21	10	6.0	1.2	18.7	16	84	7.6	5.4	15.97	11.3
LSD$_{0.5}$	1.6	1.5	0.3	0.25	0.12	0.6	0.4	0.4	0.7	0.6	2.3	0.5

***Source:** developed by the authors*

Data analysis showed that protein content in seeds ranged from 36.0% (Sigalia) to 37.5% (Gallek). The highest level of globulins was also observed in the Gallek variety, while albumins and gliadins remained relatively stable in all varieties (20-24% and 10%, respectively), indicating a balanced protein composition of the seeds. The key amino acids lysine and methionine demonstrate high nutritional value, ranging from 5.8-6.1% and 1.1-1.2%, respectively. The fat content of the seeds was 18.0-19.0%, with saturated and unsaturated acids accounting for 16% and 84%, respectively, which ensures the high technological value of the oil. Total sugars and sucrose varied depending on the variety (6.1-7.8% and 4.3-5.6%), reflecting varietal differences in nutritional value. The active symbiotic potential index (thousand kg·day/ha) was used for evaluation. The moisture content of the seeds is within the range of 11-11.5%, which allows assessing their suitability for storage and use. The calculated LSD$_{0.5}$ indicates statistically significant differences between varieties in all seed quality indicators. The data in the table show that the Gallek and ES Mentor varieties have an optimal combination of protein value, oil content and symbiotic potential, which makes them promising for cultivation in the forest-steppe zone of Ukraine. The near-infrared spectroscopy (NIR) method provided a fast, accurate and non-destructive determination of the protein, oil and amino acid composition of the seeds, which allowed for a comprehensive assessment of seed quality on an experimental scale without additional chemical analysis. The studies also demonstrated the high effectiveness of using improved plant protection systems in combination with optimised mineral nutrition. The use of biological and chemical protection agents together with foliar application of the growth regulator chlormequat chloride at concentrations of 0.5% and 0.75% had a positive effect on biometric indicators, plant resistance and productivity (Table 5).

***Table 5**. Soybean plant density before harvesting depending on variety and seed treatment, thousand plants/ha (average for 2023-2025)*

Variety	Control (untreated)	Rhizohumin-Plus, 0.5%	Rhizohumin-Plus, 0.75%
Gallek	555.7	565.5	585.9
ES Mentor	550.6	555.4	569.8
OAC Brook	548.9	553.1	566.2
Sigalia	546.3	550.6	563.7
Kobza	552.4	558.3	571.5
LSD$_{0.5}$	4.7	7.5	11.1

***Source:** developed by the authors*

Analysis of the data in Table 5 shows that the density of soybean plants before harvesting depended significantly on both varietal characteristics and the cultivation techniques used. In the control variant without seed treatment, plant density varied between 546.3 and 555.7 thousand plants/ha, reflecting the genetically determined difference between varieties in terms of initial growth intensity and plant survival during the growing season. The use of a biological preparation in combination with the growth regulator chlormequat chloride at a concentration of 0.5% provided a statistically significant increase in plant density in all studied varieties. The increase compared to the control averaged 4.0-6.2 thousand plants/ha, which indicates a positive effect of the technological method on germination energy and plant survival during vegetation.

The highest density indicators were formed when using a concentration of 0.75%, where the density of the Gallek, Kobza and ES Mentor varieties exceeded 569 thousand plants/ha. The increase compared to the control reached 14-17 thousand plants/ha, which indicates a significant positive effect of combining biological seed treatment with growth regulation. At the same time, varietal characteristics remained a determining factor in the formation of sowing density: the Gallek and Kobza varieties consistently formed a higher density regardless of the treatment option. The value of $LSD_{0.5}$ confirms the statistical significance of the differences between the variants. The results obtained indicate that the combination of biological preparations with growth regulators is an effective element of soybean cultivation technology, which contributes to the preservation of plants and creates the conditions for high yields under various soil and climatic conditions. For a comprehensive assessment of the impact of technological methods on the formation of plant production potential, it is also important to analyse symbiotic activity, the results of which are presented in Table 6.

***Table 6**. Symbiotic efficiency of soybeans depending on technological methods in the experimental field of the Department of Plant Growing of Uman National University (average for 2023-2025)*

Variety	Seed treatment	Retardant concentration, %	Tuber weight, g/plant	Active symbiotic potential, thousand kg·days/ha	Biological nitrogen fixation weight, g/plant	Biological nitrogen fixation weight, kg/ha	$LSD_{0.5}$,
ES Mentor	Control	–	221	15.72	77.38	77.38	0.91
	Rizohumin-Plus	0.5	226	15.88	77.87	77.87	
	Rizohumin-Plus	0.75	232	16.46	79.06	79.06	
Gallek	Control	–	453	19.76	117.54	117.54	0.91
	Rizohumin-Plus	0.5	470	20.32	119.87	119.87	
	Rizohumin-Plus	0.75	489	22.34	124.56	124.56	
OAC Brook	Control	–	420	15.88	92.00	92.00	0.85
	Rizohumin-Plus	0.5	435	16.30	94.50	94.50	
	Rizohumin-Plus	0.75	450	16.80	97.00	97.00	
Sigalia	Control	–	410	15.72	91.00	91.00	0.84
	Rizohumin-Plus	0.5	425	16.20	93.50	93.50	
	Rizohumin-Plus	0.75	440	16.65	96.00	96.00	
Kobza	Control	–	430	15.97	92.50	92.50	0.85
	Rizohumin-Plus	0.5	445	16.40	95.00	95.00	
	Rizohumin-Plus	0.75	460	16.90	97.50	97.50	

***Source:** developed by the authors*

Data analysis showed that the use of "Rizohumin-Plus" in combination with foliar application of the retardant contributed to an increase in nodule mass, active symbiotic potential, and biological nitrogen fixation in all studied varieties. The highest indicators for all parameters were observed at a retarder concentration of 0.75%, which indicates the stimulating effect of the technological technique on the symbiotic activity of soybeans. Among the varieties, Gallek showed the highest symbiotic efficiency, while the lowest indicators of active symbiotic potential were observed in the Sigalia variety. The calculated $LSD_{0.5}$ for the treatments demonstrates the reliability of the differences between the variants and confirms the effectiveness of the technological measures used in increasing plant productivity and adaptability. In general, the results of three years of research have shown a significant influence of the combination of varietal characteristics, weather conditions and technological methods on the formation of productivity and quality indicators of soybean seeds in the conditions of the Right-Bank Forest-Steppe of Ukraine. It was established that the most productive and stable varieties were ES Mentor and Kobza, while the highest symbiotic activity was demonstrated by the Gallek variety, especially when inoculated and treated with a 0.75% concentration of retardant. The data obtained indicate the feasibility of using integrated technological approaches that include inoculation, nutrition optimisation, and selection of varieties with high adaptive potential, which ensures stable yields even in contrasting agroclimatic conditions. The presented results can serve as a scientific basis for improving soybean cultivation technologies and formulating recommendations for production practice.

The results obtained indicate the significant role of varietal characteristics and technological techniques in the formation of soybean symbiotic efficiency, which is consistent with modern ideas about biological nitrogen fixation as a complex physiological and biochemical process. Similar patterns regarding the significant role of varietal characteristics in the formation of the symbiotic apparatus of soybeans are noted in the work of A. Korobka (2021), where it was found that modern varieties differ significantly in their response to elements of cultivation technology in organic systems. The authors emphasise that the genetically determined ability to symbiosis determines the efficiency of biological nitrogen use, which is confirmed by the results of current research, where the highest values of active symbiotic potential were recorded in the Gallek and OAC Brook varieties.

The results of studies by O. Grygor'eva *et al.* (2019) and K. Cartier (2025), conducted under irrigation conditions, also indicate a close relationship between varietal characteristics and plant response to technological techniques. The authors found that intensification of technology promotes the growth of root system biomass and nodule activity, which correlates with the observed increase in nodule mass and biologically fixed nitrogen following seed inoculation. O. Milenko *et al.* (2021), O. Revtio & O. Zolin (2023) note that the adaptive potential of modern soybean varieties is determined not only by the level of yield, but also by the efficiency of physiological processes, in particular nitrogen fixation. Their studies showed that varieties with higher ecological plasticity demonstrate more stable performance under variable growing conditions. A similar trend was observed in current study, where varieties with a higher nodule mass provided higher symbiotic potential values regardless of the treatment option.

Data from L. Bilavska & A. Rybalchenko (2020), A. Parfenuk *et al.* (2021) and B. Siamabele (2021) confirm that the variability of economically valuable traits in soybeans is largely determined by growing conditions and the biological characteristics of the variety. Although the study focused primarily on productivity, the authors note that effective nitrogen nutrition is one of the key factors in yield formation, which is consistent with the observed increase in biologically fixed nitrogen mass. The work of Y.M. Hadzalo *et al.* (2023) emphasises the importance of optimising mineral nutrition and biological factors to increase soybean productivity. The authors point out that the combination of biological and agronomic measures contributes to a more complete utilisation of the symbiotic potential of the crop. The present findings complement these findings, demonstrating that seed inoculation can effectively enhance symbiotic activity even without excessive application of mineral fertilisers. In general, the results of the studies are consistent with current scientific data and, at the same time, refine them, showing the variety-specific nature of soybean response to technological techniques. The differences identified between varieties indicate the need for a differentiated approach to the development of cultivation technology, taking into account their biological characteristics and symbiotic nitrogen fixation potential.

CONCLUSIONS

According to the results of three-year studies (2023-2025) conducted in the Right-Bank Forest-Steppe zone of Ukraine, a significant influence of hydrothermal conditions during the growing season on the growth, development, productivity and quality of soybean seeds has been established. The contrasting weather conditions during the years of research, in particular the lack of rainfall and higher temperatures in 2024 and more favourable moisture conditions in 2023 and 2025, made it possible to objectively assess the adaptive potential of the varieties studied. Among the five soybean varieties (Gallek, ES Mentor, OAC Brook, Sigalia, Kobza), ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha) provided the highest average yield for 2023-2025, which indicates their high ecological plasticity and ability to form a stable yield under changing weather conditions. The OAC Brook variety (3.09 t/ha) had slightly lower but more consistent yield indicators. The lowest average productivity over the three-year period was recorded for the Gallek (2.66 t/ha) and Sigalia (2.64 t/ha) varieties, indicating their higher sensitivity to drought and temperature stress conditions.

The fractional composition of seeds significantly depended on both varietal characteristics and weather conditions of the year. The largest share of the large fraction (>5.0 mm) according to the average indicators for 2023-2025 was formed by the varieties Gallek, ES Mentor and OAC Brook, while the variety Sigalia consistently showed an increased share of the small fraction, especially in conditions of moisture deficiency in 2024. The ES Mentor and Kobza varieties were distinguished by the highest stability of fraction composition regardless of the year of cultivation. The weight of 1,000 seeds and protein content were characterised by moderate varietal variability and relative stability over the years of research. The highest weight of 1,000 seeds was formed by the Gallek variety, while the Sigalia variety had the lowest values of this indicator, which is consistent with the high proportion of small seeds. The protein content in soybean seeds ranged from 32.0 to 34.2%, without sharp interannual changes, which indicates the genetically determined stability of this indicator. A tendency towards an inverse relationship between seed weight and protein content was established.

A comprehensive assessment of the chemical composition of seeds using near-infrared spectroscopy (NIR) showed that the Gallek and ES Mentor varieties combined high protein content, optimal amino acid composition and sufficient fat content in the seeds, which determines their high nutritional and technological value. The ES Mentor and Kobza varieties were also characterised by stable indicators of active symbiotic potential. The use of the biological preparation Rizohumin-Plus in combination with the growth regulator chlormequat chloride at concentrations of 0.5 and 0.75% contributed to an increase in plant density, symbiotic activity and crop preservation in all studied varieties. The most pronounced positive effect was observed in the varieties Gallek, ES Mentor and Kobza, which creates the conditions for increasing their production potential. In general, the results of three years of research confirm the feasibility of growing the ES Mentor and Kobza varieties as the most productive and stable in the conditions of the Right-Bank Forest-Steppe of Ukraine, while the OAC Brook variety can be recommended as plastic with balanced seed quality indicators.

ACKNOWLEDGEMENTS

None.

FUNDING

The study received no funding.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Alburaki, M., Abban, S.K., Evans, J.D., & Chen, Y.P. (2024). Occurrence and distribution of two bacterial brood diseases (American and European foulbrood) in US honey bee colonies and resistance to antibiotics from 2015 to 2022. *Journal of Apicultural Research,* 63(4), 701-710. doi: 10.1080/00218839.2024.2329854.

[2] Bilavska, L.H., & Rybalchenko, A.M. (2019). Variability of economically valuable traits of soybean in the Left-Bank Forest-Steppe of Ukraine. *Bulletin of Poltava State Agrarian Academy*, 1, 65-72. doi: 10.31210/visnyk2019.01.08.

[3] Bilavska, L.H., & Rybalchenko, A.M. (2020). Cluster analysis in soybean varieties classification by economic characteristics. *Agrobiology*, 2, 7-15. doi: 10.33245/2310-9270-2020-161-2-7-15.

[4] Cartier, K.M.S. (2025). *"Exceptional" global warming spike continued in 2024*. Retrieved from https://eos.org/articles/exceptional-global-warming-spike-continued-in-2024.

[5] Central Geophysical Observatory named after Borys Sreznevskyi. (2024). Retrieved from https://surl.li/gwkrzv.

[6] Convention on Biological Diversity. (1992, June). Retrieved from https://surl.li/rpxdhr.

[7] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1979, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.

[8] DSTU 4138-2002. (2004). *Seeds of agricultural crops. Methods for determining quality*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=91465.

[9] DSTU EN ISO 12099:2022. (2023). *Animal feed, cereals and crushed cereal products. Guidelines for the use of near-infrared spectrometry (EN ISO 12099:2017, IDT; ISO 12099:2017, IDT)*. Retrieved from https://surl.li/crvqvt.

[10] Grygor'eva, O.M., Dimova, S.B., & Almaieva, T.M. (2019). Efficiency of biological products in soybean cultivation technology on ordinary heavy loam chernozem of the Right-Bank Steppe of Ukraine. *Agricultural Microbiology,* 29, 46-55. doi: 10.35868/1997-3004.29.46-55.

[11] Hadzalo, Y.M., Vozhehova, R.A., & Likar, Y.O. (2023). Formation of biometric indicators and soybean seed yield depending on elements of agrotechnology under irrigation conditions. *Tavrian Scientific Bulletin*, 131, 46-56. doi: 10.32782/2226-0099.2023.131.6.

[12] Hen, S.P. (2022). Yield and structure of soybean harvest depending on elements of cultivation technology. *Foothill and Mountain Agriculture and Animal Husbandry*, 71(2), 100-111. doi: 10.32636/01308521.2022-(71)-2-7.

[13] Hlupak, Z.I. (2020). Optimization of soybean plant density depending on maturity group for the conditions of the northeastern part of the Forest-Steppe of Ukraine. *Bulletin of Uman National University of Horticulture*, 2, 23-25. doi: 10.31395/2310-0478-2020-2-23-25.

[14] Ivasyk, M.V., & Bakhmat, M.I. (2022). Increasing the performance of soybean grain in the conditions of Podillia. *Podilian Bulletin: Agriculture, Engineering, Economics,* 37, 51-57. doi: 10.37406/2706-9052-2022-2-8.

[15] Korobka, A.A. (2021). Dynamics of soybean production in Ukraine and the world. *Balanced Nature Management*, 4, 125-134. doi: 10.33730/2310-4678.4.2021.253098.

[16] Laslo, O.O., Marinich, L.H., & Kocherha, A.Yu. (2024). Efficiency of application of biological growth regulators on winter wheat in the conversion period to organic production. *Tavrian Scientific Bulletin,* 138, 81-87. doi: 10.32782/2226-0099.2024.138.10.

[17] Milenko, O.H., Antonets, M.O., Kopan, D.V., Dobrovolskyi, S.O., & Lukina, A.R. (2021). Yield of early-maturing soybean varieties depending on seed sowing rate. *Bulletin of Poltava State Agrarian Academy*, 4, 103-111. doi: 10.31210/visnyk2021.04.13.

[18] Parfenuk, A.I., Havryliuk, L.V., Beznosko, I.V., Pasichnik, L.P., Turovnik, Y.A., & Ternovyi, Y.V. (2021). Influence of Filazonit biopreparation on soybean seed quality. *Ukrainian Journal of Ecology,* 11(3), 86-89. doi: 10.15421/2021_148.
[19] Revtio, O.Ya., & Zolin, O.O. (2023). Features of soybean cultivation under climate change conditions (review). *Tavrian Scientific Bulletin*, 133, 105-113. doi: 10.32782/2226-0099.2023.133.15.
[20] Riabultchenko, A.M., & Serdiuk, A.Ye. (2023). Influence of varietal properties on productivity elements and soybean yield in the Left-Bank Forest-Steppe of Ukraine. *Agrarian Innovations,* 21, 88-92. doi: 10.32848/agrar.innov.2023.21.13.
[21] Siamabele, B. (2021). The significance of soybean production in the face of changing climates in Africa. *Cogent Food & Agriculture,* 7(1), article number 1933745. doi: 10.1080/23311932.2021.1933745.

Формування якості насіння сої залежно від захисту рослин у лісостепу України

Віталій Кравченко
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-4873-5367

Юрій Новак
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-2042-521X

Леся Вишневська
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0001-9470-9050

Сергій Рогальський
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0009-0007-5739-8717

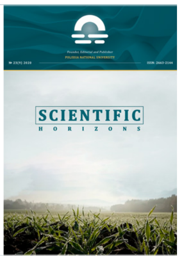
Андрій Січкар
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0009-0005-0169-8839

Анотація. Метою дослідження було встановлення закономірностей формування продуктивності та якості насіння сої залежно від погодних умов і сортових особливостей у Правобережному Лісостепу України. Польові дослідження проводили упродовж 2023–2025 рр. на дослідних ділянках Уманського району Черкаської області. Об'єктом досліджень були п'ять сортів сої різного генетичного походження та морфобіологічних особливостей: Галлек, ЕС Ментор, ОАЦ Брук, Сигалія та Кобза. Ґрунтово-кліматичні умови років досліджень суттєво відрізнялися за температурним режимом і вологозабезпеченням, що дало змогу оцінити адаптивний потенціал сортів за контрастних гідротермічних умов. Методично дослідження базувалися на польовому експерименті з обліком основних елементів структури врожаю, маси 1 000 насінин, фракційного складу насіння та показників якості. Вміст білка й олії в насінні визначали методом інфрачервоної спектроскопії, а вологість – за стандартною лабораторною методикою. Динаміку формування надземної біомаси аналізували з використанням суми ефективних температур та логістичної моделі росту. Встановлено, що у 2024 році за умов дефіциту вологи та підвищених температур темпи наростання біомаси, маса 1 000 насінин і врожайність знижувалися на 8-25 % порівняно з 2023 та 2025 роками. За середніми трирічними даними найвищу та найстабільнішу врожайність сформували сорти ЕС Ментор і Кобза, тоді як сорти Галлек і Сигалія виявилися більш чутливими до стресових умов. Якісні показники насіння мали переважно сортову детермінацію: сорт Галлек вирізнявся найбільшою масою 1 000 насінин і високою часткою крупної фракції, тоді як вміст білка та олії залишався відносно стабільним упродовж років досліджень. Практична цінність роботи полягає в обґрунтуванні доцільності добору сортів сої з високою екологічною пластичністю та стабільною якістю насіння для умов Правобережного Лісостепу України в умовах зростаючої кліматичної мінливості

Ключові слова: продуктивність сої; сортові особливості; якість насіння; цукристість; економічна ефективність; інокуляція; технологія вирощування

ISSN 2663-2144
e-ISSN 2709-8877

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 29(1), 30-40
UDC 633.15:[631.559:631.51]-042.75
DOI: 10.48077/scihor1.2026.30



Variability of corn grain yield and moisture depending on the method of tillage

Volodymyr Skoryk*
PhD in Agricultural Sciences, Lecturer
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0009-0008-8715-8826

Anna Lozinska
PhD in Agricultural Sciences, Lecturer
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0002-3421-3042

Oleksandr Karnaukh
PhD in Agricultural Sciences, Associate Professor
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-4241-6154

Article's History:
Received: 21.11.2025
Revised: 04.03.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. Optimisation of corn grain production requires a comprehensive approach to reducing technology costs. The purpose of the experiment and the research objective was to determine the optimal method and depth of primary soil tillage to reduce soil moisture losses and to substantiate the appropriate maturity group of the cultivated hybrids for the implementation of their genetic yield potential with maximum moisture release under field conditions of the central Forest-Steppe zone. The response of 11 mid-early and mid-season corn hybrids (FAO 210-350) was evaluated in 2019-2021 under different primary tillage methods – disc harrowing (up to 15 cm), ploughing (25-27 cm), and deep loosening (35-37 cm) – and yields and moisture release were compared across treatments and hybrid maturity groups. A statistically high correlation coefficient ($r = 0.74^{***}$) indicated the dependence of corn grain yield on the depth of the main tillage. Loosening at 35-37 cm provided an increase in the yield of corn grain from 0.7 to 1.6 t/ha compared to ploughing, and disc harrowing reduced the yield from -0.3 t/ha to -0.9^{*} t/ha. The yield regression equation from the ripeness group (FAO) – $y = 3.5269 + 0.0117x$ – indicated the possibility of increasing grain yield when using hybrids with a longer growing season, which was confirmed by a significant positive correlation coefficient $r = +0.86^{***}$ (73.96%). Statistically significant correlation of these features with double disc harrowing – $r = +0.42^{**}$ (17.6%), with ploughing – $r = +0.22^{**}$ (4.8%), with deep loosening – $r = +0.38^{**}$(14.4%), respectively. The trend of increasing grain moisture with increasing yield was established – $r = +0.89^{***}$ in the hybrids under study, regardless of the method of tillage. Increasing the yield of corn

Suggested Citation:
Skoryk, V., Lozinska, A., & Karnaukh, O. (2026). Variability of corn grain yield and moisture depending on the method of tillage. *Scientific Horizons*, 29(1), 30-40. doi: 10.48077/scihor1.2026.30.

*Corresponding author

grain was possible by growing later-maturing hybrids, while the moisture content of grain will also increase. The highest grain yield was provided by mid-season hybrids with Tesla (FAO 350) – 8.95 t/ha (+1.03*t/ha) and KWS 351 (FAO 350) – 8.77 t/ha (+1.6**t/ha) against the background of deep loosening of the soil at 35-37 cm with an average humidity of 16.81% and 16.28%, respectively. As a result of the experiment, it was recommended to sow in the central Forest-Steppe with mid-season corn hybrids (FAO 300-350) using deep loosening of the soil with a disc-chisel unit up to 35-37 cm as the main treatment

Keywords: corn hybrids; correlation; regression; variation coefficient; deep loosening; depth of cultivation; FAO

INTRODUCTION

An important role in implementing the genetic potential of corn is played by the presence of sufficient moisture in the root layer of the soil. Due to the specific weather conditions of the last decade, plants mainly suffer from insufficient moisture during the most critical periods of growth – from flowering to grain filling and wax maturity. The method and depth of the main tillage is a significant factor in the possibility of preserving and effectively using the existing natural moisture reserves by the plant, and given the lack of irrigation in the vast majority of the central Forest-Steppe of Ukraine, establishing the optimal method and depth of the main tillage for corn and determining hybrids with fast moisture recovery in the field and high grain yield was relevant for study.

V. Poliakov (2020) and O. Havriushenko & V. Rudas (2025) noted that an important factor influencing the value of grain yield and its quality is the sowing of corn hybrids of certain ripeness groups that are more adapted to local growing conditions, which have their own genetic characteristics. The difference in the growing season between FAO 190 and 380, according to R. Vozhehova *et al.* (2023), is up to 19-22 days, this affects the yield properties of hybrids, maturation time, and harvesting humidity. V. Palamarchuk *et al.* (2020) and M. Kyrpa *et al.* (2023) indicated differences in moisture recovery in different ripeness groups. One of the most important energy-intensive technological operations in the cultivation of corn is tillage, which is used to create comfortable conditions for the growth and development of plants in the field. S. Dolia (2024b) noted that the method and depth of primary soil tillage play an important role in the water and air permeability of the upper layers, where the root system of plants is mainly located. There was no consensus among researchers about the absolute superiority of one or another method of primary soil tillage, since this was influenced by the predecessor, soil, climatic, and weather conditions of the growing year, terms and seeding rates, and other factors.

For agricultural production in Ukraine, ploughing is the most common and traditional method of primary soil tillage, which has a number of advantages over other methods of tillage. According to specialists from the Institute of Irrigated Agriculture, under irrigation in the Steppe zone, ploughing to a depth of 25-27 cm is the most appropriate, providing up to 14.9 t/ha of corn grain compared with 11.2 t/ha with disc harrowing (Pysarenko *et al.*, 2020). The study by A. Kovalenko *et al.* (2022) on sunflower indicated that the proportion of influence of the method oftillage on the yield is 51-75% and the highest yield is achieved when using ploughing. T. Chaika *et al.* (2023) and A. Andriienko *et al.* (2025) established a differential response of soybean varieties to tillage methods, but traditional ploughing had the advantage. Conclusions of the dissertation by A. Kohan (2021) on sunflower in the Steppe zone of Ukraine, and experiments by M. Marenych & K. Koba (2024) on corn showed the superiority of ploughing over other methods of tillage. In the literature sources, there was also an alternative opinion about the method and depth of the main tillage, as evidenced by the conclusions from the experiments of other researchers on other crops. The advantage of deep tillage over surface tillage was proved by experiments of P. Pysarenko *et al.* (2020), which pointed out the advantage of deep loosening of the soil over ploughing and disc harrowing according to the phytosanitary state of crops, where the number of pathogens is lower and the yield is higher.

Thus, the purpose of the study was to investigate the influence of the method and depth of the main tillage on the yield and harvesting moisture of corn hybrids of different FAO groups and the level of variability of these characteristics in the conditions of the central part of the Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The experiment was conducted in the central part of the Forest-Steppe during the growing season of 2019-2021 in the field crop rotation of the Uman District, Cherkasy Oblast, on podzolized chernozem with a pH of 5.9-6.2 and a humus content of up to 3.1%. The predecessor was winter wheat, the seeding rate for all hybrids was 80 thousand pcs/ha, the amount of mineral fertilisers applied ($N_{114}P_{24}K_{24}S_{24}$ of active substance) and plant protection – identical for all variants of the experiment for 3 years. The temperature regime of the growing season exceeded the long-term average values of all years of the experiment. The most critical temperatures were June, July, and August. According to data from the Uman meteorological station, total precipitation during the 2019 growing season (April-August) amounted to 192 mm, in 2020 – to 232 mm, and in 2021 – to 371 mm, compared with a long-term average of 281 mm (Novak & Novak, 2022; 2023).

The subjects under study were 11 corn hybrids of various genetic origins with FAO 210-350, which were divided into conditional ripeness groups:

1. FAO 210-250 – Gran 220 (FAO 210), Gran 310 (FAO 250), DKC 3795 (st.) (FAO 250) – standard for the group;
2. FAO 260-300 – VN 63 (FAO 280), Gran 6 (FAO 300), LG 30315 (st.) (FAO 280) – standard for the group;
3. FAO 310-350 – VN 6763 (FAO 320), Amarok 290 (FAO 320), DKC 3511 (FAO 330), Tesla (FAO 350), KWS 381 (st.) (FAO 350) – standard for the group.

Variants of the experiment were three methods of primary soil tillage:

1. Option 1 (control) – classic ploughing with a skim coulter to a depth of 25-27 cm;
2. Option 2 – double disc harrowing to a depth of 12-15 cm;
3. Option 3 – combined cultivation to a depth of 35-37 cm – deep loosening of the soil with a disc-chisel unit.

The number of repetitions was 3 for each hybrid in each of the tillage options. The area of the site was 0.56 ha (500*11.2 m). Placement of plots (hybrids) within each tillage option was randomised. Corn harvesting was carried out using a combine harvester equipped with a corn header, with grain yield determined by the weighing method and recalculated into t/ha. The grain harvest moisture was determined by the Wile 55 grain moisture meter. Statistical analysis was carried out according to generally accepted methods (Yeshchenko *et al.,* 2014) with the definition of statistical indicators of the average value ($\bar{x}$), standard deviation ($S_{\bar{x}}$), coefficient of variation (CV,%), correlation coefficient (r), regression coefficient (b).

RESULTS AND DISCUSSION

The optimal duration of the harvesting period of technologically ripe grain is 10-20 days, provided that the threshing time increases, there are risks of significant losses due to lodging of plants, shedding of grain, damage by pathogens and pests. Therefore, the simultaneous maturation and moisture recovery of grain at all cobs in the array is important, which is given considerable attention by breeders (Vozkhehova *et al.,* 2021; Bibel & Chernobai, 2023). High-yielding modern corn hybrids, contained in the state register of plant varieties suitable for distribution in Ukraine (2025), provide grain yields – up to 20 t/ha, silage mass – up to 80-90 t/ha. As of 2024, the known record corn yield was 39.14 t/ha on irrigation in the United States (Corteva agriscience, 2024). In Ukraine, the real yield of grain crops reached in the Steppe conditions on irrigation from 14.2 t/ha (Hadzalo *et al.,* 2024) up to 15.6 t/ha (Skoryk & Prykhodko, 2025). In the Forest-Steppe, the yield of corn hybrids of different ripeness groups without irrigation, according to O. Mishchenko *et al.* (2024) – 9.4-12.1 t/ha, according to Z. Hlupak & A. Butenko (2022) – up to 11.4 t/ha.

The experimental data obtained indicate a difference in the yield level by year, since the weather conditions were diverse during the experiment. Average temperatures from April to September (the growing season of corn) exceeded the long-term average in all years of observation. 2019 was favourable in terms of weather conditions for the development of an average yield level by corn hybrids under study (Table 1). The beginning of the corn growing season in 2020 was optimal for plant development in terms of temperature and precipitation. In May and June, a total of 171.4 mm fell, and the average temperature contributed to the active growth of plants. But extreme high temperatures and very limited precipitation during the period of flowering and grain filling (July – August) negatively affected the development of grains, so the average yield of corn ranged from 3.4 t/ha to 7.3 t/ha for hybrids of different ripeness groups. 2021 was optimal, during the experiment period, for the maximum implementation of the genetic yield potential of the corn hybrids under study. Significantly higher than the average long-term precipitation and optimal, without sharp highs, temperatures of the growing season allowed developing a grain yield from 6.5 to 12.6 t/ha.

***Table 1**. Precipitation and average air temperature during the corn growing season, 2019-2021*

Month of the year	Precipitation, mm, by year				Average temperature, °C, by year			
	2019	2020	2021	Average long-term	2019	2020	2021	Average long-term
March	16.3	23.9	32.4	36.0	4.3	6.3	2.0	0.4
April	22.4	21.0	49.9	41.0	12.4	9.2	7.4	8.5
May	35.6	101.0	56.4	52.0	19.2	12.5	14.0	14.6
June	69.8	70.4	104.7	81.0	22.3	20.9	19.8	17.6
July	33.8	21.4	89.8	68.0	22.1	21.6	23.2	19.0
August	19.2	17.1	69.9	49.0	21.9	21.2	20.3	18.2
September	30.6	27.4	16.2	61.0	12.3	17.8	13.0	13.6
Total for the growing season of the study year	227.7	282.2	419.3	388.0				
Total for a year	376.6	478.9	641.6	586.0				

***Note:** according to the Uman weather station*

***Source:** developed by the authors based on V. Novak & A. Novak (2022; 2023)*

The results of the dispersion analysis of the obtained experimental data indicate a significant differentiation of hybrid yield depending on the method of primary soil tillage (Table 2).

***Table 2.** Average grain yield of corn hybrids based on the results of variance analysis of a two-factor experiment, 2019-2021*

Method of primary soil tillage (factor A)	Hybrid name (factor B)	Average by variant, x, t/ha	Difference by factor	
			A	B
Ploughing (25-27 cm) **(control)**	**DKC 3795 (st.)**	6.99		
	Gran 220	5.54		-1.44**
	Gran 310	6.72		-0.27
	LG 30315 (st.)	6.23		
	VN 63	6.59		0.35
	Gran 6	6.73		0.50
	KWS 381 (st.)	7.16		
	VN 6763	7.03		-0.13
	Amarok 290	6.94		-0.23
	DKC 3511	7.21		0.05
	Tesla	7.92		0.76
Disc harrowing (12-15cm)	**DKC 3795 (st.)**	6.25	-0.74	
	Gran 220	4.60	-0.94*	-1.65**
	Gran 310	6.14	-0.58	-0.11
	LG 30315 (st.)	5.90	-0.33	
	VN 63	5.80	-0.79	-0.10
	Gran 6	6.25	-0.48	0.35
	KWS 381 (st.)	6.70	-0.46	
	VN 6763	6.69	-0.34	-0.01
	Amarok 290	6.47	-0.47	-0.23
	DKC 3511	6.51	-0.70	-0.19
	Tesla	6.99	-0.94*	0.29
Loosening (35-37cm)	**DKC 3795 (st.)**	8.04	1.06*	
	Gran 220	6.59	1.05*	-1.45**
	Gran 310	7.55	0.83*	-0.49
	LG 30315 (st.)	7.71	1.47*	
	VN 63	7.45	0.86*	-0.26
	Gran 6	7.52	0.79	-0.19
	KWS 381 (st.)	8.77	1.60*	
	VN 6763	8.12	1.09*	-0.65
	Amarok 290	8.15	1.21*	-0.62
	DKC 3511	7.87	0.66	-0.89*
	Tesla	8.95	1.03*	0.19
	LSD$_{0.95}$ by factors		**0.80**	**0.78**
	LSD$_{0.99}$ by factors		**1.84**	**1.10**

Note: **, ** – significant at* $P_{0.05}$ *and* $P_{0.01}$*, respectively*
Source: *developed by the authors based on V. Skoryk & V. Prykhodko (2025)*

In comparison with the control (ploughing 25-27 cm) in the 12-15 cm disc harrowing variant, all corn hybrids under study formed a lower grain yield, within the limits of the experiment error. Significant reduction in yield, with LSD$_{0.95}$ ≥ 0.80 t/ha, found in hybrids Gran 220 (-0.94* t/ha, or -16.97%) and Tesla (-0.94* t/ha, or -11.87%) on disc harrowing compared to ploughing. When using combined deep tillage with a disc-chisel unit to a depth of 35-37 cm, the corn hybrids under study formed mainly significantly higher grain yields compared to the control. Hybrids Gran 6 (+0.79 t/ha, or +11.74%) and DKC 3511 (+0.66 t/ha, or +9.15%) gave an increase within the statistical error of the experiment. In other hybrids under study, the increase ranged from +0.83* t/ha (+12.35%) to + 1.60* t/ha (+22.35%), which is significant at $P_{0.05}$.

The average yield of corn grain in the experiment on different variants of primary soil tillage differs depending on the depth of processing. On average, according to the experiment for three years, the yield on the control version of ploughing at 25-27 cm was 6.82 t/ha, on disc harrowing at 12-15 cm – 6.21 t/ha, on deep combined cultivation – 7.88 t/ha. That is, in the conditions of the central Forest-Steppe, with an increase in the depth of the main cultivation, a significant increase in grain yield by +1.06 t/ha (+15.5%) was established during deep loosening of the soil with a combined disc-chisel unit. When using disc harrowing at 12-15 cm, the yield in the experiment decreased by an average of -0.61 t/ha (-8.9%). Similar results were obtained and described in the literature sources, where when using disc harrowing, a decrease in yield compared to ploughing was recorded by more than 20% (Dolia, 2024b).

Correlation coefficient between the depth of tillage and the average experimental yield of hybrids $r = +0.74^{***}$ significant at $P_{0.001}$ and it indicates a direct significant relationship between the yield of corn grain and the depth of the main tillage – 54.76%. The regression graph statistically confirms that with an increase in the depth of the main tillage, the yield of corn grain in this experiment increases (Fig. 1). M. Tkachenko & N. Borys (2018) in the conditions of the Right-Bank Forest-Steppe also claimed the high efficiency of chisel deep loosening of the soil when growing corn in comparison with other non-pole methods of cultivation and control ploughing. Experiments in the Steppe zone on irrigation obtained similar results and proved that with deep loosening of the soil for corn hybrids, the increase in grain yield was significant compared to ploughing and disc harrowing (Skoryk & Prykhodko, 2025).

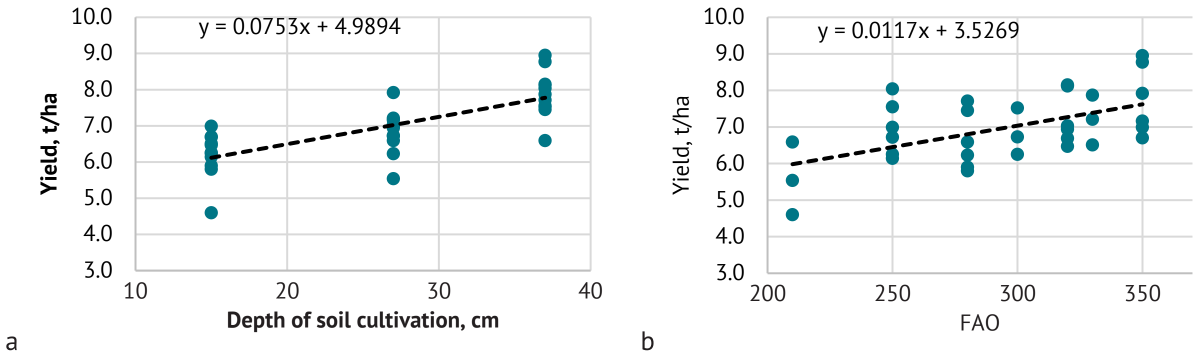


***Figure 1**. Graph of regression of corn grain yield from the depth of tillage (a) and ripeness groups (b)*
***Source:** developed by the authors based on V. Skoryk & V. Prykhodko (2025)*

Thus, deep loosening of the soil at 35-37 cm in the conditions of the central part of the Forest-Steppe provides a significant increase in the yield of corn grain (from +0.66 t/ha to $+1.60^{*}$ t/ha) in comparison with classical ploughing at 25-27 cm and has significant advantages over disc harrowing at 12-15 cm for mid-early and mid-season hybrids with FAO 210-350, which were studied in this experiment. Similar conclusions were highlighted in in the dissertation by S. Dolia (2024a), which indicates the advantage of deep loosening over chiseling and disc harrowing in optimising the agrophysical state of soils. Based on the results of the analysis of variance, it also became possible to compare the yield indicator between hybrids of different ripeness groups (Table 2). Significantly lower than the standard yield for hybrids was established in the FAO 210-250 group for Gran 220 (FAO 210). With disc harrowing, the crop shortage was -1.65^{**}t/ha (-26.40%), with ploughing – -1.44^{**}t/ha (-20.60%), with deep loosening – -1.45^{**}t/ha (-18.03%), with $LSD_{0.05} = 0.78^{*}$t/ha, and with $LSD_{0.01} = 1.10^{**}$t/ha. Gran 310 (FAO 250) in terms of grain yield was close to the standard DKC 3795 (FAO 250) within the limits of the experiment error. In the FAO 260-300 group, there was no statistically significant difference in the yield of hybrids by tillage options with a conditional standard, that is, the hybrids of this ripeness group presented in the experiment do not significantly differ in productivity among themselves.

For the FAO 310-350 group – significantly lower yield, compared to the group standard, recorded in the hybrid DKC 3511 (FAO 330) – -0.89^{*}t/ha (-10.15%) on deep loosening of the soil. Hybrids with FAO 320 – VN 6763 and Amarok 290 – produced lower than standard grain yields in all soil cultivation variants within the margin of error of the experiment. A small increase in grain yield was established for the Tesla hybrid (FAO 350): with disc harrowing –+0.29 t/ha, with ploughing – +0.76 t/ha, with deep processing – +0.19 t/ha, respectively. Hybrid Gran 6 (FAO 300) formed a higher (within the limits of the experiment error) from the conditional standard of the group yield with disc harrowing – +0.35 t/ha and on ploughing +0.50 t/ha. Hybrid VN 63 on average slightly exceeded the standard against the background of ploughing +0.35 t/ha. In general, according to the experiment, mid-season hybrids with a higher FAO – up to 350, compared to other ripeness groups, provided consistently high grain yields. The graph and regression equation are shown in Figure 1. Variation of the trait grain yield by year of the experiment differed significantly for all the hybrids under study. The largest, average coefficient of variation in grain yield against the background of the control variant was ploughing at 25-27 cm (Table 3).

***Table 3**. Variability and correlations of average values of corn grain yield and moisture according to experimental variants, 2019-2021*

Primary soil tillage options by year of testing		Grain yield at 14% humidity		Harvesting moisture of grain		Correlation coefficients between traits "grain yield – grain moisture"
		$\bar{x}$, t/ha	CV, %	$\bar{x}$, %	CV, %	
Average for the year of testing	2019	6.03	18.80	15.10	6.23	0.23**
	2020	4.62	26.28	14.70	11.29	0.18*
	2021	10.27	12.98	15.50	9.31	0.59***
	average for the experiment	**6.97**	**38.75**	**15.10**	**9.39**	**0.35****
Disc harrowing at 12-15 cm	2019	5.36	17.11	15.10	7.18	0.55**
	2020	4.02	15.90	13.83	7.31	0.10
	2021	9.23	10.88	15.00	9.66	0.61**
	average for the experiment	**6.21**	**38.32**	**14.60**	**9.01**	**0.42****
Ploughing 25-27cm	2019	6.05	17.06	15.21	4.89	0.10
	2020	3.88	16.26	15.24	11.98	0.13
	2021	10.54	10.24	15.68	9.54	0.59**
	average for the experiment	**6.82**	**43.03**	**15.40**	**9.32**	**0.22****
Loosening 35-37cm	2019	6.67	15.94	15.02	6.51	0.15
	2020	5.94	16.57	14.99	11.30	0.21
	2021	11.04	10.95	15.87	7.95	0.50**
	average for the experiment	**7.88***	**31.78**	**15.30**	**9.12**	**0.38****

Note: **, **, *** – significance of the indicator at $P_{0.05}$, $P_{0.01}$, $P_{0.001}$, respectively*

Source: *compiled by the authors*

Comparison of the coefficients of variation in grain yield and moisture by year allows indirectly assessing the influence of weather conditions on the implementation of the genetic potential of the corn hybrids under study. Thus, the highest average yield variation is in 2020 with extreme weather conditions (CV = 26.28%), and the lowest – in a favourable 2021 (CV = 12.98%). According to the variants of primary soil tillage, this reaction is similar. That is, severe extreme weather conditions of the growing year increase the variability of the grain yield trait in the corn hybrids under study, regardless of the method of tillage. The trend of the average harvesting humidity indicator is similar, and its variation in tillage methods is close to 9%, while the average values of the grain humidity indicator are very close to each other, regardless of the ripeness group. Thus, the corn hybrids under study with FAO 210-350 differed little in grain moisture at the time of harvesting over the years of study.

Correlation analysis of grain yield and moisture indicates a positive average significant relationship between these traits. The average correlation coefficient between yield and harvesting humidity in the experiment is positive and significant and amounts to r = +0.35** (or 12.3%). With disc harrowing, the correlation coefficient r = +0.42** (17.6%), with ploughing – r = + 0.22** (4.8%), with deep loosening – r = +0.38**(14.4%), respectively (Table 3), that is, regardless of the method of primary soil tillage, a higher harvesting humidity is established with a higher grain yield. The regression graph is shown in Fig. 2. The average grain moisture content in the experiment did not change significantly according to the tillage variants – from 14.6% to 15.4%, and the difference between the options was within the limits of the experiment error at $P_{0.05}$.

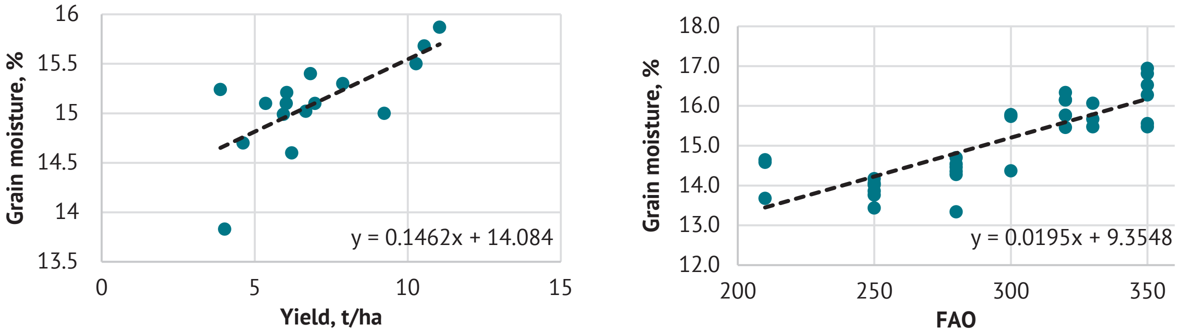


***Figure 2**. Regression graphs between features*

Source: *developed by the authors based on V. Skoryk & V. Prykhodko (2025)*

The harvesting humidity of grain and the humidity of technological ripeness are extremely important when choosing a hybrid for growing in a particular region, since the profitability of growing a crop significantly depends on these indicators. Given that the corn grain must meet the humidity indicator of 14%, information on the actual harvesting humidity of the hybrids under study is a valuable result of the experiment. Analysis of grain harvesting moisture indicators of the corn hybrids under study allows assessing the level of grain moisture loss at the time of threshing. The average values of harvesting humidity for the variants are shown in the table (Table 4).

***Table 4**. Average harvesting moisture content of corn hybrids on various variants of primary soil tillage, %, 2019-2021*

Hybrid name (factor B)	**Methods of tillage (factor A)**		
	Ploughing 25-27 cm	**Disc harrowing, 12-15 cm**	**Combined deep processing 35-37cm**
	Grain moisture content, %		
DKC 3795 (st.)	14.02	13.44	13.76
Gran 220	14.65	13.68	14.58
Gran 310	14.17	13.86	14.05
Average for the FAO group 210-250	**14.28**	**13.66**	**14.13**
LG 30315 (st.)	14.54	13.34	14.70
VN 63	14.46	14.28	14.35
Gran 6	15.78	14.37	15.74
Average for the FAO group 260-300	**14.93**	**13.99**	**14.93**
KWS 381 (st.)	16.53	15.55	16.28
VN 6763	15.76	15.46	16.15
Amarok 290	16.15	15.76	16.34
DKC 3511	16.07	15.67	15.48
Tesla	16.94	15.48	16.81
Average for the FAO group 310-350	**16.29**	**15.58**	**16.21**
$LSD_{0.95\ (by\ factor\ a)}$ = 1.03%, $LSD_{0.95\ (by\ factor\ B)}$ = 1.01%			

***Source:** developed by the authors based on V. Skoryk & V. Prykhodko (2025)*

Among the hybrids under study, there is a tendency for higher harvesting moisture of grain with an increase in the ripeness group (FAO) (Fig. 2). On the control variant with ploughing, the variation in the average value of this trait for FAO 210-250 is 14.02-14.65%, for FAO 260-300 – 14.46-15.78%, for FAO 310-350 – 15.76-16.94%, respectively. Similar conclusions were onbtained by Z. Hlupak & A. Butenko (2022) when studying hybrids of other breeding institutions. The same trend in the average humidity value was observed in the variants with disc harrowing and deep combined processing – the harvesting moisture content of grain was higher in hybrids with a longer growing season (FAO). The statistical substantiation of the experimental data of the experiment confirms a similar manifestation of the dependence of grain moisture during harvesting and the ripeness group of corn hybrids in the conclusions of Ya. Bielov (2022), who argued that as FAO increases, the moisture content of grain during harvesting is higher. There was no significant difference in the average humidity between the FAO 210-250 and FAO 260-300 groups in all variants of primary soil tillage in this experiment ($LSD_{0.95\ (factor\ B)}$ = 1.01%. This result is also similar to the conclusions of Ye. Bazylenko & T. Marchenko (2024) in the Steppe zone, which indicates that a greater difference in humidity was clearly outlined in hybrids with a longer growing season, and FAO 190-280 did not differ much in humidity at the time of harvesting, which is confirmed by this experiment in the Forest-Steppe.

Significantly higher grain moisture content on all tillage options in hybrids with FAO over 310 compared to hybrids with a shorter growing season (FAO ⩽ 300). Comparing the indicators of harvesting humidity between hybrids of different ripeness groups, it should be noted that regardless of the method of primary soil tillage and the group of ripeness of hybrids for three years of observation (2019-2021), the maximum average value did not exceed 16.94% in ploughing in the most late-maturing of the Tesla hybrids under study (FAO 350). The low harvesting humidity of corn grain over the years of the experiment was also conditioned by rather high positive temperatures and significantly lower than normal precipitation in September-October (Novak & Novak 2022; 2023). The figure graphically shows the difference in yield and harvesting humidity of the corn hybrids under study compared to the control version of ploughing during disc harrowing and deep combined primary soil tillage (Fig. 3). The control option is taken as zero (0.00).

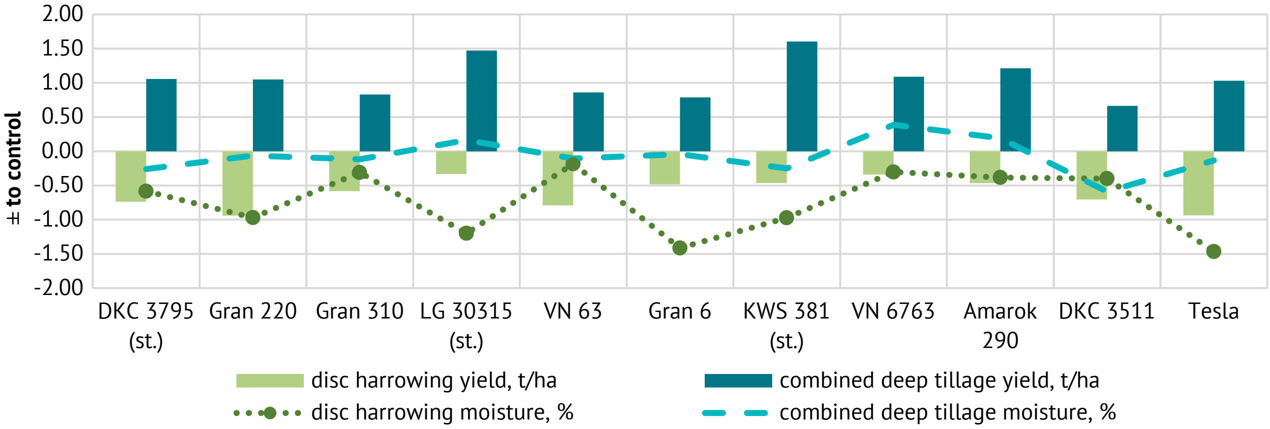


Figure 3*. Average difference (±) of grain yield and harvesting moisture in corn hybrids of different ripeness groups compared to the control variant (ploughing – taken as 0 – zero), depending on the method of primary soil tillage in 2019-2021*
Source: *developed by the authors based on V. Skoryk & V. Prykhodko (2025)*

Comparison of the average moisture content of grain during harvesting indicates a mostly low insignificant difference in the indicator for the main processing options compared to the control. It was found that the highest average harvesting humidity of grain was developed on the control version of ploughing at 25-27 cm, and with an increase or decrease in the depth of the main tillage, the harvesting humidity was lower within the limits of the experiment error. Corn hybrids with the disc harrowing variant (12-15 cm) had the lowest average grain humidity during harvesting compared to deeper processing options. Significantly lower humidity compared to the control was found with disc harrowing in hybrids LG 30315 (13.34%, or -1.2%*), Gran 6 (14.37%, or -1.41%*), Tesla (15.48, or -1.47%*). Insignificant low values of the correlation coefficients between yield and harvesting humidity in 2020 also indirectly indicate a significant influence of weather conditions of the year on the nature of changes in grain humidity in an extreme year.

The highest positive and significant values for $P_{0.01}$ were correlation coefficients in 2021. In conditions favourable for the maximum realisation of the yield potential, corn hybrids showed the highest dependence of harvesting humidity on the yield level, that is, higher grain humidity was observed in more productive hybrids with higher FAO, and in early hybrids with lower yields, lower harvesting humidity was noted. This result is similar to the data by Ya. Bielov (2022) from an experiment in the Steppe, which indicates that despite the maximum water consumption of corn –4,863 m^3/ha – harvesting moisture of grain is higher in hybrids with higher FAO. Statistical analysis establishes correlation and regression coefficients between features and defines regression equations. The relationship of the ripeness group (FAO) with the experimental average yield and experimental average humidity of corn grain of the hybrids under study is significant at $P_{0.001}$. It is determined that the correlation coefficient between FAO and yield is high positive $r = +0.86^{***}$ (regression equation – $y = 3.53 + 0.0117X$) (Fig. 1). Correlation between hybrid FAO and grain moisture of the studied samples – $r = +0.89^{***}$ (regression equation – $y = 9.36 + 0.0195X$) (Fig. 2). Therefore, in this experiment, it was established that the studied mid-early and mid-season hybrids of corn with FAO 210-350 are characterised by an increase in grain yield and an increase in harvesting humidity with the growth of FAO, that is, later hybrids form a higher yield with higher grain humidity in identical conditions. Similar results were obtained in previous experiments in the Steppe zone – V. Skoryk & V. Prykhodko (2025), and in experiments V. Poliakov (2020) found a relationship between the potential and actual yield of corn grain from the hybrid ripeness group – the larger the FAO, the higher the yield, and the yield increases from early-maturing to late-maturing. Based on the above, conclusions can be drawn that are characteristic of the cultivation conditions of mid-early and mid-season corn hybrids (FAO 210-350) under rainfed conditions in the central part of the Forest-Steppe zone of Ukraine.

CONCLUSIONS

Deep tillage at 35-37 cm with a disc-chisel unit provided a significant increase in the yield of corn of mid-early and mid-season hybrids with FAO 210-350 compared to control ploughing at 25-27 cm. Disc harrowing to a depth of 12-15 cm after the predecessor, winter wheat reduces grain yield in the studied corn hybrids and is not advisable as the main processing method. Corn hybrids with higher FAO provided an increase in grain yield with a higher percentage of humidity and identical growing conditions, which was confirmed by high significant correlation coefficients. The advantage of growing corn hybrids with FAO 320-350 in the central Forest-Steppe against the background of deep tillage with a combined disc-chisel unit, which provides a significant increase in grain yield, was substantiated.

In the conditions of the central part of the Forest-Steppe of Ukraine without irrigation, when growing corn for grain, it is recommended to carry out combined deep primary soil tillage (35-37 cm), which is optimal in the cultivation technology, and ensures the maximum implementation of the genetic potential of hybrids. Primary shallow tillage by disc harrowing to a depth of 12-15 cm is not advisable due to a significant reduction in yield compared with ploughing and deep loosening. In addition, it is recommended to give preference to modern corn hybrids with FAO 300-350, which combine high grain yield with maximum moisture output. For further study, it will be relevant to involve more than 350 corn hybrids with FAO in the study and substantiate the feasibility of using no-till and strip-till technologies in the Forest-Steppe of Ukraine.

ACKNOWLEDGEMENTS

The authors express gratitude to Serhii Voichenko, Director of the agricultural enterprise "Rodnykivka" (Uman District, Cherkasy Oblast) for providing field areas for this experiment, assistance in organising the implementation of technological operations under field conditions, which allowed conducting the experiment without deviations from the experimental methodology.

FUNDING

The study did not receive funding.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Andriienko, A., Semeniaka, I., & Andriienko, O. (2025). Influence of precursors and soil cultivation on oil and protein yield from soybean crop. *Bulletin of Agricultural Science,* 9(870), 41-50. doi: 10.31073/agrovisnyk202509-05.

[2] Bazylenko, Ye.O., & Marchenko, T.Iu. (2024). Yield and harvesting moisture content of corn hybrids at different sowing dates. *Agrarian Innovations*, 23, 7-15. doi: 10.32848/agrar.innov.2024.23.1.

[3] Bibel, Yu.O., & Chernobai, L.M. (2023). Dependence of the grain filling intensity and moisture-yielding ability on valuable economic features in corn. *Plant Breeding and Seed Production,* 124, 66-75. doi: 10.30835/2413-7510.2023.293891.

[4] Bielov, Ya.V. (2022). *Improving the technology of growing corn hybrids in conditions of the southern steppe of Ukraine*. (PhD dissertation, Mykolaiv National Agrarian University, Mykolaiv, Ukraine).

[5] Chaika, T., Lohvynenko, V., & Pshenyshnyi, A. (2023). The impact of soil tillage systems on soybean yield capacity. *Scientific Progress & Innovations*, 26(4), 54-59. doi: 10.31210/spi2023.26.04.10.

[6] Corteva agriscience. (2024). Retrieved from https://www.corteva.com.ua/.

[7] Dolia, S.M. (2024a). *Effectiveness of soil tillage methods when growing corn in the conditions of the Left Bank Forest Steppe of Ukraine*. (Doctoral dissertation, State Biotechnological University, Kharkiv, Ukraine).

[8] Dolia, S.M. (2024b). The efficiency of growing corn on grain depending on methods of primary soil tillage. *Cereals*, 8(1), 187-194. doi: 10.31867/2523-4544/0328.

[9] Hadzalo, Ya.M., Vozhehova, R.A., & Likar, Ya.O. (2024). Yield and harvesting moisture content of corn hybrids depending on the elements of agrotechnology in the conditions steppe. *Taurian Scientific Herald,* 138, 34-41. doi: 10.32782/2226-0099.2024.138.4.

[10] Havriushenko, O.O., & Rudas, V.O. (2025). The influence of some elements of cultivation technology on the productivity of corn hybrids in the conditions of the Northern Steppe of Ukraine. *Taurian Scientific Herald,* 142(1), 30-35. doi: 10.32782/2226-0099.2025.142.1.5.

[11] Hlupak, Z.I., & Butenko, A.O. (2022). The grain yield of maize hybrids depending on the ripeness group and stand density in the conditions of the forest steppe of Ukraine. *Bulletin of the Uman State University*, 2, 5-10. doi: 10.32782/2310-0478-2022-2-5-10.

[12] Kohan, A.V. (2021). *Agrotechnological foundations of increasing sunflower productivity in conditions of insufficient and unstable*. (Doctoral dissertation, Kherson State Agrarian and Economic University, Kherson, Ukraine).

[13] Kovalenko, A.M., Novokhyzhnii, M.V., Tymoshenko, H.Z., Piliarskyi, V.H., & Kazanok, O.O. (2022). Productivity and water consumption of sunflower depending on the place in crop rotation and tillage. *Agronomist.* Retrieved from https://www.agronom.com.ua/produktyvnist-i-vodospozhyvannya-sonyashnyku-zalezhno-vid-mistsya-v-sivozmini-ta-obrobitku-gruntu/.

[14] Kyrpa, M., Bodenko N., & Kulyk, V. (2023). The quality of the seeds of corn hybrids depending on the method of their collection and drying. *Bulletin of Agrarian Science*, 101(2), 65-71. doi: 10.31073/agrovisnyk202302-09.

[15] Marenych, M., & Koba, K. (2024). The impact of tillage on the yield of maternal lines of maize hybrids. *Scientific Progress & Innovations,* 27(1), 19-23. doi: 10.31210/spi2024.27.01.03.

[16] Mishchenko, O.V., Hanhur, V.V., & Danilenko, Ye.V. (2024). The formation of the productivity of corn hybrids depending on the density of plants in the conditions of the Left Bank Forest Steppe. *Scientific Progress & Innovations*, 27(2), 16-21. doi: 10.31210/spi2024. 27.02.03.

[17] Novak, V.H., & Novak, A.V. (2022). Agricultural meteorology terms 2020-2021. Agricultural year from data of weather-station Uman. *Bulletin of the Uman National University of Horticulture,* 1, 23-26. doi: 10.31395/2310-0478-2022-1-23-26.

[18] Novak, V.H., & Novak, A.V. (2023). Agricultural meteorology terms 2020-2021. Agricultural year from data of weather-station Uman. *Bulletin of the Uman National University of Horticulture*, 103(1), 153-160. doi: 10.32782/2415-8240-2023-103-1-153-160.

[19] Palamarchuk, V.D., Didur, I.M., Kolisnyk, O.M., & Alieksieiev, O.O. (2020). *Aspects of the modern technology of growing high-starch corn in the conditions of the right-bank forest-steppe*. Vinnytsia: “Druk” LLC.

[20] Poliakov, V. (2020). *Yield of corn hybrids depending on plant density and fertilization system*. doi: 10.31473/2305-5987-2020-2-27(41)-22.

[21] Pysarenko, P.V., Maliarchuk, A.S., Kuts, H.M., Biliaieva, I.M., & Myshukova, L.S. (2020). The influence of water regime and tillage methods on corn productivity. *Agronomist*. Retrieved from https://www.agronom.com.ua/vplyv-vodnogo-rezhymu-ta-sposobiv-obrobitku-gruntu-na-produktyvnist-kukurudzy/.

[22] Skoryk, V.V., & Prykhodko, V.O. (2025). The influence of the norm of sowing corn seeds on the realization of the genetic potential of hybrids under irrigation conditions of the southern Steppe of Ukraine. *Taurian Scientific Herald*, 142(2), 93-102. doi: 10.32782/2226-0099.2025.142.2.13.

[23] State register of plant varieties suitable for distribution in Ukraine. (2025). Retrieved from https://sops.gov.ua/en/.

[24] Tkachenko, M., & Borys, N. (2018). The influence of hydrothermic climate change and method basic cultivation for corn productivity on grain. *Propozitsia*. Retrieved from https://propozitsiya.com/articles/tekhnolohiyi-vyroshchuvannya/vplyv-hidrotermichnykh-zmin-klimatu-ta-sposobu-osnovnoho.

[25] Vozhehova, R.A., Lavrynenko, Yu.O., Marchenko T.Iu., Voiagkipa, LV., Sharii, V.O., & Bidnyna, I. O. (2023). Comparative analysis of yield formation of corn hybrids of different FAO groups under drip irrigation. *Agrarian Innovations*, 18, 24-31. doi: 10.32848/agrar.innov.2023.18.3.

[26] Vozhehova, R.A., Lavrynenko, Yu.O., Marchenko, T.Iu., Piliarska, O.O., Zabara, P.P., & Sakhatskyi, H.I. (2021). Morphological indicators of corn hybrids of different FAO groups depending on the elements of technology under irrigation conditions. *Agrarian Innovations*, 8, 91-99. doi: 10.32848/agrar.innov.2021.8.14.

[27] Yeshchenko, V.O., Kopytko, P.H., Kostohryz, P.V., & Opryshko, V.P. (2014). *Fundamentals of scientific research in agronomy*. Vinnitsa: PE “Edelweiss and K”.

Мінливість урожайності та вологості зерна кукурудзи залежно від способу обробітку ґрунту

Володимир Скорик
Кандидат сільськогосподарських наук, старший викладач
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0009-0008-8715-8826

Анна Лозінська
Кандидат сільськогосподарських наук, старший викладач
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0002-3421-3042

Олександр Карнаух
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-4241-6154

Анотація. Оптимізація виробництва зерна кукурудзи вимагає комплексного підходу до скорочення витрат на технологію. Визначити оптимальний спосіб та глибину основного обробітку ґрунту для зниження втрат ґрунтової вологи та обґрунтувати необхідну групу стиглості вирощуваних гібридів у реалізації генетичного потенціалу врожайності зерна з максимальною вологовіддачею в польових умовах центрального Лісостепу було метою проведеного досліду та актуальним для вивчення. Визначено реакцію 11 середньоранніх та середньостиглих гібридів кукурудзи (ФАО 210-350) в 2019-2021 рр. за різних способів основного обробітку ґрунту – дискування (до 15 см), оранка (25-27см), глибоке розпушування (35-37 см) і проведено порівняння урожайності та вологовіддачі по варіантам і групам стиглості гібридів. Статистично високий коефіцієнт кореляції ($r = 0{,}74^{***}$) вказував на залежність урожайності зерна кукурудзи від глибини основного обробітку ґрунту. Розпушування на 35-37 см забезпечувало прибавку урожайності зерна кукурудзи від 0,7 до 1,6 т/га в порівнянні з оранкою, а дискування знижувало урожайність від -0,3 т/га до $-0{,}9^{*}$ т/га. Рівняння регресії урожайності від групи стиглості (ФАО) – $y = 3{,}5269 + 0{,}0117x$ – показало на можливість збільшення урожайності зерна при використанні гібридів з довшим періодом вегетації, що підтверджено істотним позитивним коефіцієнтом кореляції $r = +\,0{,}86^{***}$ (73,96 %). Статистично істотний кореляційний зв'язок цих ознак при дворазовому дискуванні – $r = +\,0{,}42^{**}$ (17,6 %), на оранці – $r = +\,0{,}22^{**}$ (4,8 %), на глибокому розпушуванні – $r = +\,0{,}38^{**}$ (14,4 %) відповідно. Встановлена тенденція підвищення вологості зерна при зростанні урожайності – $r = +\,0{,}89^{***}$ у вивчених гібридів незалежно від способу обробітку ґрунту. Підвищення урожайності зерна кукурудзи можливе шляхом вирощування більш пізньостиглих гібридів, при цьому вологість зерна також буде збільшуватись. Найвищу урожайність зерна забезпечили середньостиглі гібриди з Тесла (ФАО 350) – 8,95 т/га ($+1{,}03^{*}$т/га) та КВС 351 (ФАО 350) – 8,77 т/га ($+1{,}6^{**}$т/га) на фоні глибокого розпушування ґрунту на 35-37см з середньою вологістю 16,81 % та 16,28 % відповідно. В результаті проведеного досліду рекомендовано проводити посів в центральному Лісостепу середньостиглими гібридами кукурудзи (ФАО 300-350) з використанням глибокого розпушування ґрунту дисколаповим агрегатом до 35-37 см як основного обробітку

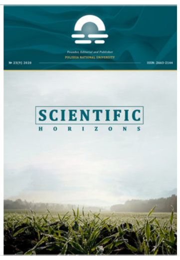
Ключові слова: гібриди кукурудзи; кореляція; регресія; коефіцієнт варіації; глибоке розпушування; глибина обробітку; ФАО

ISSN 2663-2144
e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 29(1), 41-51

UDC 633.13:632.954
DOI: 10.48077/scihor1.2026.41



Regulation of the weed component in the maize phytocoenosis using herbicides for the sustainable functioning of agroecosystems

Tetiana Tymoshchuk*
PhD in Agricultural Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0001-8980-7334

Oleh Kharchuk
LLC "Syngenta UA"
03022, 120/4 Kozatska Str., Kyiv, Ukraine
https://orcid.org/0009-0008-6466-3803

Article's History:
Received: 28.10.2025
Revised: 20.02.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. Maize is a crop with low competitive ability against weeds, especially at the early stages of growth and development. The problem of weed infestation in maize crops during the critical period of vegetation remained one of the key factors and led to a substantial reduction in the realisation of the crop yield potential. The purpose of the study was to evaluate the effectiveness of herbicide application for regulating the weed component in the maize phytocoenosis and its impact on yield formation. The research was conducted during 2024-2025 under the conditions of Biryt Shevchenko LLC in Zhytomyr region on soddy medium-podzolic soils. The effectiveness of herbicides for regulating segetal vegetation in the phytocoenosis of three maize hybrids depending on the timing and application rates was highlighted. The combined application of the pre-emergence herbicide Primextra TZ Gold and the post-emergence herbicide Elumis ensured a reduction in the number of grass and broadleaf weeds in the maize phytocoenosis. The highest indicators of weed reduction were recorded at Primextra TZ Gold rates of 4.0-4.5 L/ha in combination with Elumis at 1.75-2.0 L/ha. Differences in weed infestation of phytocoenoses among hybrids were established, in particular higher values in the hybrid SY Fortago compared with SY Phenomen and SY Marimba. The combined use of Primextra TZ Gold (3.5-4.5 L/ha) and Elumis (1.75-2.0 L/ha) ensured effectiveness at the level of 94-98% control of grass and broadleaf weeds in crops of maize hybrids. The combined application of Primextra TZ Gold (4.0 L/ha) and Elumis (1.75 L/ha) ensured the maximum grain yield of the maize hybrids SY Phenomen (9.82 t/ha) and SY Marimba (10.08 t/ha). The highest productivity of the hybrid SY Fortago (9.16 t/ha) was ensured by applying the combination of Primextra TZ Gold (4.0 L/ha) and Elumis (1.5 L/ha). The obtained results could be used to develop and scientifically substantiate effective strategies for the control of segetal plants in

Suggested Citation:
Tymoshchuk, T., & Kharchuk, O. (2026). Regulation of the weed component in the maize phytocoenosis using herbicides for the sustainable functioning of agroecosystems. *Scientific Horizons*, 29(1), 41-51. doi: 10.48077/scihor1.2026.41.

**Corresponding author*

maize phytocoenoses aimed at reducing weed infestation during the critical period of crop development and ensuring the sustainable functioning of agroecosystems

Keywords: agrocenosis; segetal vegetation; grain yield; synergism; ecological sustainability; herbicide load; control strategy

INTRODUCTION

Maize belongs to agricultural crops with low competitive ability against weeds, especially at the early stages of growth and development. In the period from emergence to the formation of 5-7 leaves, maize plants were characterised by slow growth rates, weak development of the root system, and insufficient canopy closure, which created favourable conditions for the intensive development of segetal vegetation. Under such conditions, weeds more effectively used moisture, nutrients, and light, thereby suppressing the growth and development of crop plants. The most negative impact of weeds on maize yield formation was observed during the critical period of competition, which occurred at the stages from 3-4 to 8-10 leaves. Weed infestation of crops during this period led to suppression of growth processes, a reduction in the assimilating surface area, and disturbances in the formation of generative organs, which caused a substantial decrease in the potential productivity of the crop (Anand *et al.,* 2025). Even short-term competition with weeds during the critical period of maize development could lead to a significant yield reduction that was not compensated in subsequent phases of plant growth and development, even after the complete removal of the weed component. In this regard, timely and effective control of weed infestation at the early stages of vegetation was a decisive factor in realising the genetic potential of maize productivity.

Weeds compete with crop plants for light, moisture, and nutrients, suppress their growth and development, and worsen the phytosanitary condition of crops, which resulted in a reduction in yield and product quality (Gerasko *et al.*, 2024; Hurmanchuk *et al.*, 2025). According to R. Absy (2019), R. Idziak *et al.* (2022), weed infestation of maize crops led to a reduction in grain yield from 30 to 93% depending on the weather conditions in the years of research. It was established that the combined application of a mixture of terbuthylazine, mesotrione, and S-metolachlor provided the highest effectiveness of weed control and promoted stable formation of grain yield. According to the researchers R. Idziak & Z. Woznica (2020), effective control of a wide spectrum of weeds was ensured by the use of combined herbicides containing several active substances with different mechanisms. The use of such products made it possible to minimise crop injury due to lower doses and reduced chemical residues in plants and soil. In addition, the use of a combination of herbicides with different mechanisms of action slowed the development of resistant weed species and simultaneously reduced costs for plant protection.

In the work of Yu. Skatula & R. Ostapchuk (2023), the effectiveness of herbicide application in maize agrocenoses and their impact on the level of weed infestation of crops was highlighted. The effects of different herbicide protection schemes on the formation of the weed component and crop productivity were analysed. The expediency of using herbicides to reduce competition with segetal vegetation and to increase the efficiency of maize cultivation was established. According to R. Hutianskyi & V. Zuza (2022), herbicide application substantially reduced weed infestation (by 61-65% and 80%), improved plant growth and development, and ensured an increase in maize grain yield by 2.72 t/ha under the conditions of the Eastern Forest-Steppe of Ukraine. In the study by V. Yukhymuk *et al.* (2022), the features of interaction and the effectiveness of weed control in maize crops under the use of herbicide tank mixtures were investigated. The authors found that combining active substances with different mechanisms of action increased the level of control of segetal vegetation and ensured the stability of herbicide protection of the crop.

In the study by O. Gurmanchuk *et al.* (2020), the effectiveness of post-emergence herbicides (rimsulfuron, 250 g/kg, and florasulam 6.25 g/L + 2-ethylhexyl ester of 2,4-D 452.5 g/L) and their tank mixtures for regulating the presence of segetal plants in maize crops was evaluated. It was established that separate application of herbicides reduced weed infestation by 47.5-56.1%, whereas their mixtures reduced weed infestation by 92.5%. This ensured the maximum maize yield of 5.7 t/ha, which exceeded the control without herbicides by 3.0 t/ha. According to S. Shevchenko *et al.* (2025), the combination of nicosulfuron (40 g/ha) with 2,4-D and florasulam ensured a reduction in the number of annual weed species by 91%. Y. Tkalich *et al.* (2023) emphasised that effective weed control during the critical period of yield formation substantially reduced competition for resources and thereby contributed to higher maize productivity. The studies by N. Shokalo & V. Beletskyi (2022) also noted that post-emergence herbicides provided high effectiveness of weed control and positively affected yield under conditions of a mixed type of weed infestation.

In this regard, studies on the effectiveness of modern herbicides and the assessment of their influence on maize yield formation became important, which was a key factor in increasing agroecosystem productivity, strengthening food security, and implementing the principles of sustainable agricultural development.

Therefore, the purpose of the study was to evaluate the effectiveness of herbicide application for regulating the weed component in the maize phytocoenosis and its impact on crop yield formation.

MATERIALS AND METHODS

Field research was conducted during 2024-2025 under the conditions of the experimental field of Biryt Shevchenko LLC, located in Radulyn village, Zviahel district, Zhytomyr region. The soil of the experimental plots was soddy medium-podzolic and was characterised by the following indicators: humus content (according to Tiurin and Kononova (DSTU 7855:2015, 2016)) – 2.5%; easily hydrolysable nitrogen (according to Kornfield (DSTU 7863:2015, 2016)) – 63-79 mg/kg of soil; mobile phosphorus (according to Chirikov (DSTU 4115-2002, 2003)) – 74-85 mg/kg of soil; exchangeable potassium (according to Chirikov (DSTU 4115-2002, 2003)) – 83-92 mg/kg of soil; pHсол – 5.6-5.9 (DSTU ISO 10390:2021, 2022). The climate of the region where the research was conducted was temperate continental, with a cool winter and a moderately warm summer. Winters were characterised by frosts and an average temperature below 0°C. The average winter temperature (December-February) ranged within -1 to -5°C, with mean minimum values of about -6 to -8°C in the coldest months. The average temperature in the summer months varied within +18...+25°C. The mean annual precipitation amounted to 530-600 mm. Precipitation was distributed throughout the year, with a maximum in the summer months. Weather conditions during the maize vegetation periods differed from long-term averages. The experimental design included the following factors:

- Factor A – maize hybrid (SY Phenomen FAO 220, SY Marimba FAO 240, SY Fortago FAO 260);
- Factor B – application of a soil herbicide at different rates (control without treatment; Primextra TZ Gold 500 SC at 3.5 L/ha; Primextra TZ Gold 500 SC at 4.0 L/ha; Primextra TZ Gold 500 SC at 4.5 L/ha);
- Factor C – application of a post-emergence herbicide at different rates (control without treatment; Elumis 105 OD at 1.5 L/ha; Elumis 105 OD at 1.75 L/ha; Elumis 105 OD at 2.0 L/ha).

Primextra TZ Gold 500 SC is a combined soil herbicide of selective systemic action intended for effective control of the main annual grass and broadleaf weeds in the phytocoenoses of agricultural crops. It combined two active substances with different mechanisms of action: S-metolachlor (312.5 g/L) and terbuthylazine (187.5 g/L). S-metolachlor blocked cell division in young seedlings, while terbuthylazine suppressed photosynthetic processes, which led to weed death before emergence or immediately after crop emergence.

Elumis 105 OD is a selective systemic post-emergence herbicide intended to control a wide spectrum of annual and perennial grass and broadleaf weeds in maize crops. Developed and produced by Syngenta, the product combined two active substances with different biochemical mechanisms of action: mesotrione (75 g/L) and nicosulfuron (30 g/L). The product had systemic action; therefore, after application to weed leaves, active molecules penetrated tissues, moved via xylem and phloem, and blocked key metabolic processes. Mesotrione inhibited carotenoid biosynthesis, which resulted in chlorophyll degradation, chlorosis, and tissue necrosis. Nicosulfuron inhibited amino acid synthesis by blocking enzymes involved in acetolactate synthase synthesis, which prevented normal growth and cell division in meristematic tissues of weeds. This combination made it possible to integrate a rapid foliar effect with prolonged systemic suppression of segetal plants. Elumis effectively prevented the emergence of several weed flushes during the vegetation period and reduced competition with the crop for resources. The studied products were developed and produced by Syngenta Ukraine.

The plot size was 100 m^2. The experiment had four replications, and plot arrangement was systematic. The maize cultivation technology was generally accepted for the research zone. Soybean was the preceding crop. Primary tillage involved ploughing with a Kverneland RN 100 plough to a depth of 25-27 cm, followed by pre-sowing cultivation with a Case IH Tiger-Mate 255 cultivator to a depth of 6-8 cm. Sowing of maize hybrids was carried out in the third ten-day period of April using a Kverneland Optima TF Profi planter with a target stand density of 80 thousand plants per 1 hectare. The soil herbicide Primextra TZ Gold 500 SC was applied immediately after sowing. Post-emergence application of the herbicide Elumis 105 OD was carried out at the 4-5-leaf stage of maize (the third ten-day period of May) using a Berthoud Raptor 4240 sprayer equipped with injector twin-fan nozzles. The working solution rate was 250 L/ha.

The study used a field method to assess the effect of herbicides on weed infestation and maize yield; an accounting method to determine weed density on experimental plots; a gravimetric method to determine crop yield indicators; and a mathematical-statistical method to process and interpret the obtained experimental data. During the vegetation period, phenological observations of maize plant growth and development were carried out. Herbicide phytotoxicity was assessed using a 9-point scale, where 1 point corresponded to complete plant death and 9 points corresponded to the absence of visual damage symptoms. On accounting plots with an area of 10 m^2, the total number of segetal plants and their numbers by groups were recorded and compared with the untreated control. The species composition of weed plant communities in the maize phytocoenosis was determined using generally accepted methods with the use of identification guides, atlases, and reference materials (Veselovsky *et al.,* 1988). The effectiveness of herbicide action was calculated before harvesting. The effectiveness of herbicide application was assessed by analysing the accounting results and comparing them with the control variant in which herbicide treatment was not performed. The effectiveness of herbicide action in maize crops was calculated using a widely known formula. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979). Mathematical processing of the research results was performed by analysis of variance and correlation–regression analysis on a personal computer using specialised application software packages such as MS Excel.

RESULTS

The use of soil and post-emergence herbicides enabled the control of a wide spectrum of annual and perennial grass and broadleaf weeds, ensuring crop protection during the critical period of its growth. Timely application of herbicides contributed to the formation of an optimal phytosanitary situation, reduced weed competition with maize plants, and increased the efficiency of moisture and nutrient use. The results of weed counts before harvest indicated a substantial dependence of herbicide protection effectiveness on the application rate of the product and the characteristics of the maize hybrid (Table 1).

***Table 1**. Weed infestation of the maize phytocoenosis depending on the timing and application rates of herbicides, mean for 2024-2025*

Hybrid (Factor A)	Pre-emergence application of Primextra TZ Gold 500 SC, CS, L/ha (Factor B)	Post-emergence application of Elumis 105 OD, MD, L/ha (Factor C)	Number of weeds, plants/m^2		
			grass	broadleaf	total
SY Phenomen	Control	–	18.5	22.3	40.8
	3.5	Control	3.2	8.7	11.9
	4.0	Control	2.8	7.5	10.3
	4.5	Control	2.5	6.9	9.4
	3.5	1.5	0.8	1.5	2.3
	3.5	1.75	0.5	1.2	1.7
	3.5	2.0	0.3	1.0	1.3
	4.0	1.5	0.6	1.3	1.9
	4.0	1.75	0.4	1.0	1.4
	4.0	2.0	0.2	0.8	1.0
	4.5	1.5	0.7	1.4	2.1
	4.5	1.75	0.5	1.1	1.6
	4.5	2.0	0.3	0.9	1.2
SY Marimba	Control	–	16.2	20.1	36.3
	3.5	Control	2.9	7.8	10.7
	4.0	Control	2.5	6.7	9.2
	4.5	Control	2.2	6.1	8.3
	3.5	1.5	0.7	1.3	2.0
	3.5	1.75	0.4	1.0	1.4
	3.5	20	0.2	0.8	1.0
	4.0	1.5	0.5	1.1	1.6
	4.0	1.75	0.3	0.8	1.1
	4.0	2.0	0.1	0.6	0.7
	4.5	1.5	0.6	1.2	1.8
	4.5	1.75	0.4	0.9	1.3
	4.5	2.0	0.2	0.7	0.9
SY Fortago	Control	–	20.1	25.5	45.6
	3.5	Control	3.5	9.5	13.0
	4.0	Control	3.0	8.2	11.2
	4.5	Control	2.7	7.6	10.3
	3.5	1.5	0.9	1.7	2.6
	3.5	1.75	0.6	1.4	2.0
	3.5	2.0	0.4	1.2	1.6
	4.0	1.5	0.7	1.5	2.2
	4.0	1.75	0.5	1.2	1.7
	4.0	2.0	0.3	1.0	1.3
	4.5	1.5	0.8	1.6	2.4
	4.5	1.75	0.6	1.3	1.9
	4.5	2.0	0.4	1.1	1.5

***Source:** compiled by the authors*

In the control treatment, a high level of weed infestation of the crops was recorded, both by annual grass weeds (*Echinochloa crus-galli* L., *Setaria pumila* (Poir.) Roem. & Schult.) and by annual broadleaf weeds (*Chenopodium album* L., *Amaranthus retroflexus* L., *Ambrosia artemisiifolia* L.). The results of weed density assessments in maize crops indicated a substantial effect of both the separate and the combined use of herbicides on the formation of the phytosanitary status of the agrocenosis. In the untreated control (without chemical protection), a high level of weed infestation was recorded, which depended on the maize hybrid and ranged from 36.3 plants/m^2 in the hybrid SY Marimba to 45.6 plants/m^2 in the hybrid SY Fortago. This indicated differences in the competitive ability of hybrids against weeds.

Pre-emergence application of Primextra TZ Gold at rates of 3.5, 4.0, and 4.5 L/ha ensured a substantial reduction in weed density compared with the control. At the same time, partial re-establishment of certain broadleaf weed species was observed during the vegetation period. Under this application approach, the number of annual grass weeds decreased more effectively, whereas the density of broadleaf species remained relatively higher, especially in the second half of vegetation. Increasing the rate of Primextra TZ Gold contributed to a reduction in the total number of weeds; however, the difference between the rates of 4.0 and 4.5 L/ha was minor. Post-emergence application of Elumis at the studied rates (1.5, 1.75, and 2.0 L/ha) ensured a substantial reduction in the density of both grass weeds and broadleaf weeds during the maize vegetation period. Increasing the application rate from 1.5 to 2.0 L/ha contributed to higher effectiveness in controlling late-emerging weeds and to an expanded spectrum of susceptible species.

The highest level of herbicide protection effectiveness was ensured by combining pre-emergence application of Primextra TZ Gold with post-emergence application of Elumis. In this treatment, a sharp and statistically significant reduction in the density of both grass weeds and broadleaf weeds was observed ($p \leqslant 0.05$). The total number of weeds decreased to 0.7-1.5 plants/m^2 depending on the hybrid and the application rates, which indicated a synergistic action of the soil and post-emergence herbicides. With an increase in the post-emergence rate of Elumis from 1.5 to 2.0 L/ha, higher effectiveness in controlling late-emerging weeds and an expanded spectrum of controlled species were recorded, primarily among broadleaf weeds. At the same time, the combinations Primextra TZ Gold 4.0-4.5 L/ha with Elumis 1.75-2.0 L/ha proved to be optimal in terms of effectiveness and rational use. The analysis of the hybrid effect showed that the hybrid SY Marimba was characterised by the lowest level of weed infestation across all protection treatments, whereas in the crops of the hybrid SY Fortago a higher number of weeds was consistently recorded. This confirmed the expediency of considering hybrid-specific characteristics when developing the herbicide protection system for maize. The results of calculations of herbicide effectiveness for regulating the presence of the weed component in the agrocenosis of maize of different hybrids depending on the timing and application rates are presented in Table 2.

***Table 2**. Effectiveness of herbicide application in the maize phytocoenosis depending on the timing and application rates, mean for 2024-2025*

Hybrid (Factor A)	Pre-emergence application of Primextra TZ Gold 500 SC, CS, L/ha (Factor B)	Post-emergence application of Elumis 105 OD, MD, L/ha (Factor C)	Number of weeds, plants/m^2		
			grass	broadleaf	total
SY Phenomen	Control	–	–	–	–
	3.5	Control	82.70	60.99	70.83
	4.0	Control	84.86	66.37	74.75
	4.5	Control	86.49	69.06	76.96
	3.5	1.5	95.68	93.27	94.36
	3.5	1.75	97.30	94.62	95.83
	3.5	2.0	98.38	95.52	96.81
	4.0	1.5	96.76	94.17	95.34
	4.0	1.75	97.84	95.52	96.57
	4.0	2.0	98.92	96.41	97.55
	4.5	1.5	96.22	93.72	94.85
	4.5	1.75	97.30	95.07	96.08
	4.5	2.0	98.38	95.96	97.06
SY Marimba	Cotrol	–	–	–	–
	3.5	Control	82.10	61.19	70.52
	4.0	Control	84.57	66.67	74.66
	4,5	Control	86.42	69.65	77.13
	3.5	1.5	95.68	93.53	94.49
	3.5	1.75	97.53	95.02	96.14
	3.5	2.0	98.77	96.02	97.25

Table 2. Continued

Hybrid (Factor A)	Pre-emergence application of Primextra TZ Gold 500 SC, CS, L/ha (Factor B)	Post-emergence application of Elumis 105 OD, MD, L/ha (Factor C)	Number of weeds, plants/m^2		
			grass	broadleaf	total
SY Marimba	4.0	1.5	96.91	94.53	95.59
	4.0	1.75	98.15	96.02	96.97
	4.0	2.0	99.38	97.01	98.07
	4.5	1.5	96.30	94.03	95.04
	4.5	1.75	97.53	95.52	96.42
	4.5	2.0	98.77	96.52	97.52
SY Fortago	Control	–	–	–	–
	3.5	Control	82.59	62.75	71.65
	4.0	Control	85.07	67.84	75.60
	4.5	Control	86.57	70.20	77.58
	3.5	1.5	95.52	93.33	94.51
	3.5	1.75	97.01	94.51	95.82
	3.5	2.0	98.01	95.29	96.70
	4.0	1.5	96.52	94.12	95.38
	4.0	1.75	97.51	95.29	96.48
	4.0	2.0	98.51	96.08	97.36
	4.5	1.5	96.02	93.73	94.95
	4.5	1.75	97.01	94.90	96.04
	4.5	2.0	98.01	95.69	96.92

Source: *compiled by the authors*

Pre-emergence application of Primextra TZ Gold ensured a high level of weed control in the maize agrocenosis; in particular, the effectiveness of control of annual grass weeds ranged from 82.1 to 86.57%, whereas that of broadleaf weeds ranged from 60.99 to 70.2%. Increasing the application rate from 3.5 to 4.5 L/ha led to a gradual increase in control effectiveness, especially for broadleaf species. Post-emergence application of Elumis markedly increased the effectiveness of weed control in the phytocoenoses of all studied hybrids. In combination with pre-emergence application of Primextra TZ Gold, the effectiveness of control of grass weeds reached 98-99%, broadleaf weeds 95-97%, and overall effectiveness amounted to 94-98%. The highest values were observed at the Elumis rate of 2.0 L/ha. Combined application of the products (pre-emergence + post-emergence) demonstrated a synergistic effect, ensuring the maximum possible level of weed control, including late-emerging flushes and a broad spectrum of species. This confirmed the expediency of an integrated approach to herbicide protection in maize to ensure the ecological sustainability of agricultural systems.

The highest herbicide effectiveness for weed control at the same application rates and timing was recorded in the hybrid SY Marimba, whereas the lowest was recorded in SY Fortago, which indicated differences in the competitive ability of plants against weeds and the need for a differentiated approach to selecting herbicide rates. Maximum weed control was achieved with the combination of Primextra TZ Gold 4.0-4.5 L/ha and Elumis 1.75-2.0 L/ha, which ensured a 96-98% reduction in total weed density in maize crops regardless of the hybrid. Application of the herbicides Primextra TZ Gold and Elumis ensured an increase in grain yield of the maize hybrids SY Phenomen, SY Marimba, and SY Fortago (Table 3).

***Table 3**. Productivity of maize hybrids depending on the timing and application rates of herbicides (mean for 2024-2025)*

Hybrid (Factor A)	Pre-emergence application of Primextra TZ Gold 500 SC, CS, L/ha (Factor B)	Post-emergence application of Elumis 105 OD, MD, L/ha (Factor C)	Yield, t/ha	Increase relative to the control	
				t/ha	%
SY Phenomen	Control	–	4.85	–	–
	3.5	Control	8.52	3.67	75.67
	4.0	Control	8.79	3.94	46.24
	4.5	Control	8.65	4.36	49.60
	3.5	1.5	9.21	4.36	50.40
	3.5	1.75	9.48	4.63	50.27
	3.5	2.0	9.35	4.5	47.47
	4.0	1.5	9.55	4.7	50.27
	4.0	1.75	9.82	4.97	52.04
	4.0	2.0	9.68	4.83	49.19

Table 3. Continued

Hybrid (Factor A)	Pre-emergence application of Primextra TZ Gold 500 SC, CS, L/ha (Factor B)	Post-emergence application of Elumis 105 OD, MD, L/ha (Factor C)	Yield, t/ha	Increase relative to the control	
				t/ha	%
SY Phenomen	4.5	1.5	9.42	4.57	47.21
	4.5	1.75	9.65	4.8	50.96
	4.5	2.0	9.51	4.66	48.29
SY Marimba	Control	–	5.21	–	–
	3.5	Control	8.93	3.72	71.40
	4.0	Control	9.17	3.96	76.01
	4.5	Control	9.05	3.84	73.70
	3.5	1.5	9.58	4.37	83.88
	3.5	1.75	9.79	4.58	87.91
	3.5	2.0	9.65	4.44	85.22
	4.0	1.5	9.85	4.64	89.06
	4.0	1.75	10.08	4.87	93.47
	4.0	2.0	9.92	4.71	90.40
	4.5	1.5	9.71	4.5	86.37
	4.5	1.75	9.95	4.74	90.98
	4.5	2.0	9.80	4.59	88.10
SY Fortago	Control	–	4.53	–	–
	3.5	Control	8.19	3.66	80.79
	4.0	Control	8.45	3.92	47.86
	4.5	Control	8.32	3.79	44.85
	3.5	1.5	8.87	4.34	52.16
	3.5	1.75	9.09	4.56	51.41
	3.5	2.0	8.95	4.42	48.62
	4.0	1.5	9.16	4.63	51.73
	4.0	1.75	9.02	4.49	49.02
	4.0	2.0	8.89	4.36	48.34
	4.5	1.5	9.03	4.5	50.62
	4.5	1.75	8.90	4.37	48.39
	4.5	2.0	8.77	4.24	47.64

Source: *compiled by the authors*

Pre-emergence application of Primextra TZ Gold had a substantial effect on maize yield. In the phytocoenoses of all maize hybrids, the use of the soil herbicide at application rates of 3.5, 4.0, and 4.5 L/ha ensured a grain yield increase of 3.66 to 4.36 t/ha compared with the control (without treatment), which amounted to 44.85-76.01%. Increasing the application rate of the product resulted in a slight increase in yield, especially in the hybrids SY Phenomen and SY Marimba. Post-emergence application of Elumis in combination with Primextra TZ Gold substantially increased grain yield. The highest increase was ensured by the hybrid SY Marimba, where, with the application of the combination Primextra 4.0 L/ha and Elumis 1.75 L/ha, the yield reached 10.08 t/ha, which exceeded the control by 93.47%. For the other hybrids, the yield increase under combined protection amounted to 47-52%.

Combined application of the soil and post-emergence herbicides ensured a synergistic effect, which contributed to a stable increase in grain yield of maize hybrids compared with treatments involving only pre-emergence application. This confirmed the expediency of an integrated approach to herbicide protection in maize to maximise crop productivity. The highest grain yields were recorded in the hybrids SY Phenomen (9.82 t/ha) and SY Marimba (10.08 t/ha) under combined application of Primextra TZ Gold (4.0 L/ha) and Elumis (1.75 L/ha). The maximum grain yield of the hybrid SY Fortago (9.16 t/ha) was obtained with the application of the combination Primextra TZ Gold (4.0 L/ha) and Elumis (1.5 L/ha). Therefore, herbicide protection was an important element of the protection strategy and a necessary condition for effective maize cultivation. In addition, the rational use of modern combined herbicides, taking into account the species composition of weeds, crop development stages, and environmental conditions, made it possible to reduce the herbicide load on the agroecosystem, minimise negative environmental impacts, and ensure stable maize productivity.

DISCUSSION

The obtained results were consistent with Ukrainian and international studies, which reported that maize was one of the crops most sensitive to weed infestation during the first 30 to 40 days of vegetation, and that yield losses in the absence of effective weed control could exceed 30 to 50% (Yoshitha *et al.*, 2025). The high level of weed infestation in the control treatments recorded in the experiment (36.3 to 45.6 plants/m^2) corresponded to values reported by researchers who noted the dominance of annual grass weeds and broadleaf weeds in maize crops in the absence of herbicide protection (Gurmanchuk *et al.*, 2020). In the study by S. Okrushko (2019), it was indicated that soil herbicides effectively controlled annual grass weeds and early-emerging broadleaf species; however, their protective effect could weaken in the second half of vegetation, particularly under favourable conditions for repeated weed emergence. A similar tendency was also observed in this study, where, under separate pre-emergence application of Primextra TZ Gold, re-establishment of broadleaf weeds was noted, and increasing the product rate did not always ensure a proportional increase in effectiveness.

According to the findings of B. Wiqar *et al.* (2021), the most stable weed control in maize crops was achieved under an integrated use of soil and post-emergence herbicides. This was also supported by the results of the present research, where the combination of Primextra TZ Gold with post-emergence application of Elumis reduced total weed density to 0.7 to 1.5 plants/m^2. Similar effectiveness indicators were reported in studies devoted to the use of mesotrione and nicosulfuron for controlling both grass weeds and broadleaf weeds, including late-emerging flushes (Mitkov *et al.*, 2022). The literature also indicated that the level of weed infestation depended on the crop hybrid (Kryvulko, 2025). This was associated with differences in the intensity of early growth, leaf canopy architecture, and the competitive ability of plants. The differences identified in this study between hybrids, in particular the higher level of weed infestation in the crops of the hybrid SY Fortago compared with SY Phenomen and SY Marimba, fully agreed with these provisions and confirmed the need to adapt herbicide schemes to the biological characteristics of specific hybrids.

The obtained results regarding the effectiveness of herbicide weed control in maize crops were consistent with data reported in the literature. Thus, in field studies by V. Gurtovenko and O. Tsyuk (2024), the use of soil herbicides demonstrated a high level of weed suppression at the early stages of maize growth. The effectiveness of control of grass weeds and broadleaf weeds 14 days after application reached up to 87%, and after 40 days up to 75%, which corresponded to the present results, where pre-emergence application of the soil herbicide ensured a weed control level above 70% in the experimental treatments. The results of combined weed control, when post-emergence herbicides complemented the soil action of Primextra, were also supported by the study of S. Soroka (2025). In the studies by V. Sudak *et al.* (2021), it was noted that post-emergence products could provide high control effectiveness depending on weed species composition and application conditions, and that maximum values were achieved when combined with soil products, which expanded the spectrum of controlled species and prolonged the duration of the protective effect.

The research by O. Milenko *et al.* (2022) on the effectiveness of Elumis 105 OD also emphasised its high efficacy in controlling both grass weeds and broadleaf weeds during the phase of active maize vegetation, particularly when applied at optimal timings, namely at the 2 to 8 leaf stages of the crop. This supported the observations regarding the high level of weed control in treatments with post-emergence herbicide application. Therefore, the obtained data not only corresponded to existing scientific sources regarding the high effectiveness of soil and post-emergence herbicides in maize protection systems, but also highlighted the practical expediency of the combined use of herbicides to achieve the maximum level of weed control, which was consistent with the recommendations of modern agronomic technologies (Sudak *et al.*, 2021).

The data of H. Alptekin *et al.* (2023) confirmed that weed control intensity and maize yield were closely related to the selected herbicide protection schemes, and that the use of herbicide combinations was effective for achieving consistently high yield levels, which supported the appropriateness of the schemes selected in this study. The findings obtained in the present experiment on the effect of herbicide protection on maize yield were consistent with the published study by M. Devkota *et al.* (2024), which confirmed the positive role of herbicides in increasing crop productivity. Thus, field experiments by O. Markovska *et al.* (2024) indicated that the application of soil and post-emergence herbicides substantially reduced above-ground weed biomass and contributed to a significant increase in grain yield in research where comprehensive herbicide protection schemes were applied. An increase in grain yield under the integrated use of soil and post-emergence protection was also observed in this study. Consequently, the results not only confirmed well-established regularities of herbicide weed control in maize crops, but also complemented the literature data regarding the expediency of the combined application of soil and post-emergence herbicides while taking into account hybrid-specific characteristics.

CONCLUSIONS

Post-emergence application of Elumis at rates of 1.5 to 2.0 L/ha significantly reduced the density of grass weeds and broadleaf weeds in maize crops ($p \leqslant 0.05$). Increasing the rate to 2.0 L/ha ensured more effective control of late-emerging weeds. Weed density assessments showed that combining pre-emergence application of Primextra TZ Gold (3.5 to 4.5 L/ha) with post-emergence application of Elumis (1.5 to 2.0 L/ha) ensured a substantial reduction in the total number of grass weeds and broadleaf weeds in maize crops compared with the control ($p \leqslant 0.05$). The highest effectiveness of weed control was recorded under the combined use of the products at Primextra TZ Gold rates of 4.0 to 4.5 L/ha and Elumis rates of 1.75 to 2.0 L/ha, where weed density decreased to 0.7 to 1.5 plants/m^2. The effectiveness of herbicide protection varied depending on the maize hybrid; in the crops of the hybrid SY Fortago, a tendency towards higher weed infestation was recorded compared with the hybrids SY Phenomen and SY Marimba.

Pre-emergence application of Primextra TZ Gold (3.5 to 4.5 L/ha) ensured 71 to 77% effectiveness of weed control in maize crops. Its combination with the post-emergence herbicide Elumis (1.5 to 2.0 L/ha) increased effectiveness to 94 to 98%, ensuring control of both grass weeds and broadleaf weeds, including late-emerging flushes. The highest effectiveness was observed at the Elumis rate of 1.75 to 2.0 L/ha. The combined application of Primextra TZ Gold (4.0 to 4.5 L/ha) and Elumis (1.75 to 2.0 L/ha) ensured the formation of the maximum grain yield of the maize hybrids SY Phenomen (9.82 t/ha) and SY Marimba (10.08 t/ha). The highest grain yield of the hybrid SY Fortago (9.16 t/ha) was obtained under the integrated application of Primextra TZ Gold (4.0 L/ha) and Elumis (1.5 L/ha). This highlighted the expediency of a differentiated approach to herbicide protection. Further research should be directed towards optimising herbicide protection technologies for maize, taking into account the species structure of segetal vegetation, soil and climatic conditions, and minimising the herbicide load, with the aim of forming resilient agrophytocoenoses.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Absy, R. (2019). Weed control efficiency of some pre-and post-emergence herbicides in maize. *Journal of Plant Production*, 10(12), 1037-1042. doi: 10.21608/JPP.2019.69816.

[2] Alptekin, H., Ozkan, A., Gurbuz, R., & Kulak, M. (2023). Management of weeds in maize by sequential or individual applications of pre-and post-emergence herbicides. *Agriculture*, 13(2), article number 421. doi: 10.3390/agriculture13020421.

[3] Anand, G., Arshdeep, S., Kritika, S.A., Guttikonda, P.S., Zeeshan, A.S., Shimpy, S., Sanchit, T., & Iza, F. (2025). Evaluating the impact of pre- and post-emergence herbicides on weed dynamics and sustainable Maize cultivation practices. *Plant Science Today,* 12(2), 1-9. doi: 10.14719/pst.7353.

[4] Convention on Biological Diversity. (1992, June). Retrieved from https://surl.li/cwcrar.

[5] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1979, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.

[6] Devkota, M., Sai, R., Shrestha, A., Chaudhary, S., Koirala, P., & Mahato, M. (2024). Weed management effects on weed dynamics, yield and economics of spring maize at Dang, Nepal. *Turkish Journal of Agriculture – Food Science and Technology*, 12(s1), 1997-2008. doi: 10.24925/turjaf.v12is1.1997-2008.6865.

[7] DSTU 4115-2002. (2003). *Soils. Determination of mobile phosphorus and potassium compounds using the modified Chirikov method*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=58863&utm.

[8] DSTU 7855:2015. (2016). *Soil quality. Determination of group gumus composition on method of Tjurin in Kononova and Belchikova's updating*. Retrieved from https://surl.li/pmnepq.

[9] DSTU 7863:2015. (2016). *Soil quality. Determination of available hydrolyzable nitrogen by Kornfild method*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=62745&utm.

[10] DSTU ISO 10390:2022. (2022). *Soil, treated biowaste, and sludge. Determination of pH (ISO 10390:2021, IDT)*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=97744.

[11] Gerasko, T., Tymoshchuk, T., Moisiienko, V., Hrytsiuk, N., & Alekseeva, T. (2024). Phytocoenotic assessment of herbaceous plant communities in the organic sweet cherry orchard. *Scientific Horizons*, 27(5), 32-50. doi: 10.48077/scihor5.2024.32.

[12] Gurmanchuk, O., Plotnytska, N., Nevmerzhytska, O., Pavliuk, I., Tymoshchuk, T., & Bondareva, L. (2020). Control of weed component in maize crops when applying postemergent herbicides. *Scientific Horizons*, 23(7), 53-58. doi: 10.33249/2663-2144-2020-92-7-53-58.

[13] Gurtovenko, V., & Tsyuk, O. (2024). Efficiency of application of soil herbicides on sunflower crops. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(3). doi: 10.31548/dopovidi.3(109).2024.008.

[14] Hurmanchuk, O., Plotnytska, N., Nevmerzhytska, O., Hrytsiuk, N., & Tymoshchuk, T. (2025). Control of segetal vegetation in the agrocenosis of common buckwheat. *Scientific Horizons*, 28(10), 85-92. doi: 10.48077/scihor10.2025.85.

[15] Hutianskyi, R., & Zuza, V. (2022). The efficiency of application of post-emerging herbicides in corn sowing in the Eastern Forest Steppe of Ukraine. *Bulletin of Agricultural Science*, 9(834), 34-42. doi: 10.31073/agrovisnyk202209-04.

[16] Idziak, R., & Woznica, Z. (2020). Efficacy of reduced rates of soil-applied dimethenamid-P and pendimethalin mixture followed by postemergence herbicides in maize. *Agriculture,* 10(5), article number 163. doi: 10.3390/agriculture10050163.

[17] Idziak, R., Waligóra, H., & Szuba, V. (2022). The influence of agronomical and chemical weed control on weeds of corn. *Journal of Plant Protection Research*, 62(2), 215-222. doi: 10.24425/jppr.2022.141362.

[18] Kryvulko, M.V. (2025). Degree of sunflower crops weed infestation under various plant protection systems. *Feeds and Feed Production*, 99, 127-135. doi: 10.31073/kormovyrobnytstvo202599-11.

[19] Markovska, O.Ye., Dudchenko, V.V., Pikovskyi, M.Y., & Mechet, A.O. (2024). Phytosanitary condition of maize agrocoenosis depending on measures to regulate pest organisms in the conditions of the Northern Steppe of Ukraine. *Taurida Scientific Herald,* 140, 165-175. doi: 10.32782/2226-0099.2024.140.22.

[20] Milenko, O.H., Solod, I.S., Mohylat, P.H., Hryn, M.E., & Veherenko, V.S. (2020). Effectiveness of post-emergence herbicides application on reas of corn grown for grain. *Bulletin of Poltava State Agrarian Academy*, 4, 86-92. doi: 10.31210/visnyk2020.04.10.

[21] Mitkov, A., Yanev, M., Neshev, N., Tityanov, M., & Tonev, T. (2019). Herbicide control of the weeds in maize (*Zea mays* L.). *Scientific Papers. Series A. Agronomy*, LXII(1), 368-373.

[22] Okrushko, S. (2019). Adjustment of weeds in corn crops. *Young Scientist*, 2(66), 319-322. doi: 10.32839/2304-5809/2019-2-66-69.

[23] Shevchenko, S.M., Shevchenko, M.S., Derevenets-Shevchenko, K.A., Kozechko, V.I., & Zavertaliuk, O.V. (2025). The impact of systematic herbicide application on maize grain yield. *Podilian Bulletin: Agriculture, Engineering, Economics*, 46, 136-142. doi: 10.37406/2706-9052-2025-1.19.

[24] Shokalo, N.S., & Beletskyi, V.O. (2022). Application of post-emergence herbicides in corn crops for grain. *Taurida Scientific Herald,* 123, 153-158. doi: 10.32851/2226-0099.2022.123.21.

[25] Skatula, Yu.M., & Ostapchuk, R.V. (2023). Effectiveness of herbicides in corn agrocenoses. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 19(5). doi: 10.31548/dopovidi5(105).2023.009.

[26] Soroka, S.Y. (2025). Assessment of the level of weed intensity of corn hybrid crop crops depending on the application of herbicides and various plant densities. *Agriculture and Foresty,* 2(37), 219-228. doi: 10.37128/2707-5826-2025-2-19.

[27] Sudak, V., Horbatenko, A., Semenov, S., & Kulyk A. (2021). Testing of herbicidal systems for maize cultivation in the Steppe of Ukraine. *Quarantine and Plant Protection*, 2, 32-36. doi: 10.36495/2312-0614.2021.2.32-36.

[28] Tkalich, Y., Kolesnykova, K., & Nazarenko, M. (2023). Effectiveness of herbicides and plant growth regulators in corn crops. *Agrology*, 5(3), 97-103. doi: 10.32819/021115.

[29] Veselovsky, I.V., Lysenko, A.K., & Manko, Y.P. (1988). *Weed identifier atlas*. Kyiv: Urozhay.

[30] Wiqar, B., Noori, M.S., & Amini, S.Y. (2021). Effects of weed management on agronomic performance and productivity of hybrid maize (*Zea mays* L.). *Journal of Agriculture and Applied Biology,* 2(2), 70-75. doi: 10.11594/jaab.02.02.01.

[31] Yoshitha, S., Sagar, L., & Reddy, M.D. (2025). Management of weeds in summer maize (*Zea mays* L.) by pre and post emergence herbicides. *Plant Science Today*, 12(1). doi: 10.14719/pst.3209.

[32] Yukhymuk, V.V., Radchenko, M.P., Sytnik, S.K., & Morderer, Y.Y. (2022). Effects of interaction and effectiveness of weed control when using tank mixtures of herbicides in maize crops. *Regulatory Mechanisms in Biosystems*, 13(2), 114-120. doi: 10.15421/022216.

Регулювання бур'янового компоненту у фітоценозі кукурудзи за використання гербіцидів для сталого функціонування агроекосистем

Тетяна Тимощук
Кандидат сільськогосподарських наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0001-8980-7334

Олег Харчук
ТОВ «Сингента Україна»
03022, 120/4 вул. Козацька, м. Київ, Україна
https://orcid.org/0009-0008-6466-3803

Анотація. Кукурудза є культурою з низькою конкурентною здатністю щодо бур'янів, особливо на ранніх етапах росту та розвитку. Проблема забур'яненості посівів кукурудзи у критичний період вегетації залишається одним із ключових факторів, призводить до істотного зниження реалізації потенціалу врожайності культури. Метою досліджень було оцінити ефективність застосування гербіцидів для регулювання бур'янового компоненту у фітоценозі кукурудзи та їх вплив на формування врожайності культури. Дослідження проводили протягом 2024-2025 рр. в умовах ТОВ «Біріт ім. Шевченка» Житомирської області на середньо підзолистих дернових ґрунтах. Висвітлено ефективність гербіцидів для регулювання сегетальної рослинності у фітоценозі трьох гібридів кукурудзи залежно від строків і норм внесення. Комбіноване застосування досходового гербіциду Примекстра TZ Голд та післясходового гербіциду Елюміс забезпечило зниження кількості злакових і дводольних бур'янів у фітоценозі кукурудзи. Найвищі показники зниження кількості бур'янів відмічено за норм Примекстра TZ Голд 4,0-4,5 л/га у поєднанні з Елюмісом 1,75-2,0 л/га. Встановлено відмінності забур'яненості фітоценозів різних гібридів, зокрема вищі показники у гібрида СИ Фортаго порівняно з СИ Феномен та СИ Марімба. Комбіноване застосування гербіцидів Примекстра TZ Голд (3,5-4,5 л/га) і Елюміс (1,75-2,0 л/га) забезпечило ефективність на рівні 94-98 % контролю злакових і дводольних бур'янів у посівах гібридів кукурудзи. Комбіноване застосування гербіцидів Примекстра TZ Голд (4,0 л/га) і Елюміс (1,75 л/га) забезпечило максимальну урожайність зерна кукурудзи гібридів СИ Феномен (9,82 т/га) і СИ Марімба (10,08 т/га). Найвищу продуктивність гібриду СИ Фортаго (9,16 т/га) забезпечило внесення комбінації Примекстра TZ Голд (4,0 л/га) і Елюміс (1,5 л/га). Отримані результати можуть бути використані для розробки та наукового обґрунтування ефективних стратегій контролю сегетальних рослин у фітоценозах кукурудзи, спрямованих на зниження рівня забур'яненості в критичний період розвитку культури та забезпеченню сталого функціонування агроекосистем

Ключові слова: агроценоз; сегетальна рослинність; урожайність зерна; синергізм; екологічна стійкість; гербіцидне навантаження; стратегія контролю

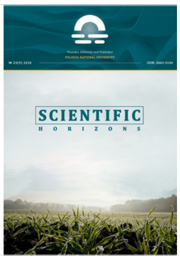
ISSN 2663-2144 e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 29(1), 52-65

UDC 633.34:631.5:631.52:631.95:519.876.5 DOI: 10.48077/scihor1.2026.52



Formation of soybean yield depending on varietal characteristics and agrotechnological practices based on predictive modelling

Igor Labunskyi

Postgraduate Student
Bila Tserkva National Agrarian University
09117, 8/1 Soborna Sq., Bila Tserkva, Ukraine
https://orcid.org/0009-0009-3201-4064

Mykola Grabovskyi*

Doctor of Agricultural Sciences, Professor
Bila Tserkva National Agrarian University
09117, 8/1 Soborna Sq., Bila Tserkva, Ukraine
https://orcid.org/0000-0002-8494-7896

Article's History:
Received: 29.09.2025
Revised: 24.02.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. The article presented the results of a two-year field experiment investigating the influence of varietal characteristics, agrotechnological practices, and weather conditions on soybean yield using predictive modelling. The relevance of the study stems from the need to improve the stability of soya bean yields in the context of climate change and the importance of using biological plant protection products (biofungicides). The aim was to establish the effectiveness of various pre-sowing seed treatment schemes and foliar application of fungicides and micronutrients, as well as to develop mathematical models for predicting soyabean yield depending on weather conditions. Field studies were conducted in 2024-2025 at the Training and Production Centre of Bila Tserkva National Agrarian University using soybean varieties 'RGT Salsa' and 'RGT Saidina'. The experiment included 50 variants. It was established that the highest average yield (2.71 t/ha) was obtained for the variety 'RGT Saidina' under the combined use of the fungicides Maxim XL, Apron XL, the inoculant BioMAG Soya, and double application of the fungicide Kolosal Pro with micronutrient fertilisers Intermag Molybdenum and Quantum Bor Active at the budding stage (BBCH 51-59) and the flowering stage (BBCH 60-69). Under this scheme, variants with the biofungicide Fitosporin-M Soya provided a yield of 2.65 t/ha, confirming the high effectiveness of biological protection. Mathematical modelling revealed a high level of agreement between actual and calculated data (error up to 0.07 t/ha). Cluster analysis of the 50 studied variants based on soybean grain yield identified three main groups according to productivity level. The first cluster included variants with yields above 2.5 t/ha, most of which combined the use of the inoculant BioMAG Soya with the fungicides Maxim XL (1.0 L/t) + Apron XL (0.5 L/t), as well as the fungicide Kolosal Pro and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active. The practical value

Suggested Citation:
Labunskyi, I., & Grabovskyi, M. (2026). Formation of soybean yield depending on varietal characteristics and agrotechnological practices based on predictive modelling. *Scientific Horizons*, 29(1), 52-65. doi: 10.48077/scihor1.2026.52.

*Corresponding author

of the results lies in identifying optimal combinations of biological and chemical fungicides, inoculants, and micronutrient fertilisers to increase soybean productivity, as well as in the possibility of forecasting yield based on climatic indicators

Keywords: inoculation; fungicides; variety; micronutrient fertilisers; climatic conditions; clustering

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the most important grain legume crops in the world, playing a key role in providing protein and vegetable oils for both the food and feed sectors. W.M. Singer *et al.* (2023) and D.B. Shelke *et al.* (2023) noted that the growing demand for this crop necessitates improving the efficiency of its cultivation through the enhancement of agrotechnologies. In this context, optimisation of soybean growing conditions in modern agroecosystems is of particular importance. Under current conditions of climatic instability and agricultural intensification, optimisation of agronomic practices for soybean cultivation becomes especially significant. In particular, according to O. Milenko *et al.* (2022), an important direction is the study of the influence of varietal characteristics in combination with different schemes of seed treatment with fungicides and inoculants, as well as foliar application of fungicides and micronutrient fertilisers. As noted by I. Prymak *et al.* (2025), determining the effectiveness of these measures makes it possible to increase yield, improve product quality, and reduce risks associated with adverse weather conditions.

At the same time, the effectiveness of these agrotechnical measures largely depends on the influence of abiotic factors, particularly water regime. Leguminous crops are highly sensitive to drought, both during vegetative and reproductive stages of development. The yield of agricultural crops, including legumes, is the result of a complex interaction between the genetic potential of the plant and a set of environmental factors. Grain productivity of legumes is also determined by symbiotic performance, which depends on the efficiency of symbiosis formed with highly active and virulent strains of nodule bacteria. In the studies of M. Nadeem *et al.* (2019), the efficiency of legume-rhizobial symbiosis under unfavourable growing conditions depends on the ability of the host plant to induce its antioxidant defence systems. This leads to adaptive changes in plant metabolism and increases their tolerance. The most noticeable effects of drought conditions on legumes include reduced germination, delayed growth, severe damage to the photosynthetic apparatus, decreased photosynthetic productivity, and reduced nutrient uptake. Accordingly, the study of plant responses and the formation of adaptive potential in crops, particularly soybean, under climate change conditions has both economic and agronomic significance.

Given the need to account for climatic factors on soya bean yields, the role various forecasting methods is increasing. One of the promising approaches to improving soybean productivity is the application of elements of mathematical modelling, which allows prediction of potential yield depending on climatic conditions. This is particularly relevant in view of increasing weather variability, which often makes it difficult to assess risks in advance and plan cultivation technologies. Crop yield modelling is an important tool for evaluating the impact of climatic factors on productivity. Researchers such as H. Chen *et al.* (2020) have used statistical methods together with process-based models to assess the impact of climate change on crop yields.

At the same time, the development of such models is associated with a number of methodological difficulties. As noted by L.B. Jaques *et al.* (2022), attempts to develop physiologically based soybean yield models over large areas have been complicated by the lack of a growth-stage model capable of accounting for these responses and applicable across a wide geographical and climatic range. T.D. Setiyono *et al.* (2021) developed a soybean phenological model, which uses nonlinear functions of temperature and photoperiod and separates flowering induction and post-induction phases to simulate flowering time. In the studies of J.Q. Zhang *et al.* (2019), the artificial neural network method provided the highest accuracy in predicting soybean phenological development stages, indicating that this approach can be effectively applied in modelling. However, according to A. Moreira *et al.* (2023) and K.R. Hopper (2023), the problem of modelling soybean growth and yield lies in the complexity of accurately describing plant responses to stress factors (drought, temperature anomalies) and the specific nature of symbiotic nitrogen fixation, which often leads to errors in traditional models under changing climatic conditions. In addition, existing systems require continuous and complex calibration for new varieties and local growing conditions.

Thus, improving the efficiency of soybean cultivation requires a comprehensive approach that incorporates both technica and analytical tools. Comprehensive studies of soybean cultivation technology components are necessary to achieve a balance between plant protection against harmful organisms, preservation of nitrogen-fixing potential, and maintenance of resilience to abiotic stress factors. The development of mathematical models for specific soil and climatic conditions makes it possible to predict the influence of weather on plant development and forecast yield. This enables the adaptation of soybean cultivation techniques, minimise climatic risks and ensure stable economic efficiency. The aim of the research was to establish the effectiveness of various pre-sowing seed treatment regimens using fungicides and inoculants, and the foliar application of fungicides and micronutrients, as well as to develop mathematical models for forecasting soyabean yield depending on weather conditions.

LITERATURE REVIEW

Under current climate change conditions, according to the Food and Agriculture Organisation of the United Nations (FAO, 2021), crop yields could fall by more than 50% of their potential productivity, which could pose serious food security challenges. As noted in their works by G.L. Hartman *et al*. (2011) and A.Y. Bandara *et al*. (2020), realising the potential productivity of leguminous crops is one of the main tasks in ensuring their high yield and is determined by a harmonious combination of all modern methods: organisational and economic, agrotechnical, immunological, biological and chemical. Among agrotechnical measures, pre-sowing seed treatment is of particular importance. As noted by N. Strom *et al*. (2020), one of the important technological practices used in soybean cultivation is pre-sowing seed treatment with fungicides, as yield losses due to damage to soybeans by phytopathogens can reach up to 40%. Subsequent studies focused on combining various elements of this technology. Studies by J.R. Rathjen *et al*. (2020) and Z. Getachew & L. Abeble (2021) investigated the combined use of seed inoculation with nodule-forming bacteria and fungicides to regulate the metabolism of leguminous crops and enhance their tolerance to fungal diseases and productivity. And according to data obtained by I. Fedoruk *et al*. (2021), combining the inoculation process with the use of micronutrient fertilisers in cultivation technology yields significant results and increases soyabean yield. This is linked to the specific functioning of the symbiotic system of leguminous crops. Research by O. Mazur *et al*. (2025) established that to maximise the development of the symbiotic system's parameters – including the number and mass of nodules, their intensive functioning with the formation of the highest levels of total and active symbiotic potential, as well as the amount of biologically fixed nitrogen – it is necessary to combine pre-sowing seed treatment (with the HighCot Super inoculant, Wonder Micro microfertiliser and Maxim XL seed dressing) with foliar feeding using chelated fertilisers containing macro- and microelements (Wonder Yellow and Wonder Blue), alongside the application of mineral fertilisers at the standard rate of $N_{20}P_{20}S_9$.

Practical aspects of implementing these processes are reflected in the results of field studies. According to V. Petrychenko *et al*. (2024), the use of pre-sowing seed treatment with a bacterial preparation based on nodule-forming bacterial strains had a lesser effect on laboratory germination and a greater effect on the germination energy of soyabeans. The highest value was obtained for the Slavna soyabean variety – 93.4% – when using nitrogen-fixing bacteria (Rhizolin + Rhizosavei) in pre-sowing seed treatment. S. Didorenko *et al*. (2023), under agroclimatic conditions of Kazakhstan, found that treating soybean seeds with molybdenum and cobalt salts before sowing is economically beneficial for the early-maturing variety Ivushka and the mid-maturing variety Lastivka. For the early-maturing variety Birlik KV, the highest profitability was recorded with combined seed treatment using the nitrogen-fixing inoculant HiStick and Mo and Co salts. In the soybean variety Zhansaya, additional seed treatments reduced production profitability.

Alongside biological factors, the plant nutrition system plays an important role. According to the work of S. Bagale (2021), effective management of the soybean nutrition regime helps to provide the necessary nutrients for the plant without causing a significant reduction in yield, and also helps the crop to withstand biotic and abiotic stresses. A total of fifteen nutrients are required for the growth and development of soya. These nutrients can be classified as micro- and macronutrients. Macronutrients required in quantities >0.01% include nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). They perform structural and functional roles in plants. Similarly, soya also requires micronutrients, but in quantities of <0.01%. These are copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), chlorine (Cl), molybdenum (Mo) and nickel (Ni). These micronutrients perform enzymatic and cellular regulatory functions. In practice, the supply of these elements to plants is often achieved through foliar fertilisation. According to studies by V. Petrychenko *et al*. (2016), the most effective way to provide plants with micronutrients is foliar feeding during the growing season at critical stages of soybean development: the 3-5 trifoliate leaf stage, budding, and pod formation. In this way, up to 100% of the plant's micronutrient requirements can be satisfied.

The effectiveness of such approaches is confirmed by a number of experimental studies. A.V. Golodna *et al*. (2024) found that foliar feeding of soybean plants with the organo-mineral fertiliser Khelprost Soya at the branching and budding stages, against the background of fertilisation $N_{15}P_{45}K_{60} + N_{30}$ and pre-sowing seed treatment, increased yield to 3.67 and 3.74 t/ha (by 23.2% and 25.5%, respectively) and provided a yield increase compared to the absolute control of 0.69 t/ha and 0.76 t/ha. Fertilisation at the flowering stage ensured soybean seed yield at the level of 3.62 t/ha, with a yield increase of 0.64 t/ha. Under the conditions of the Forest-Steppe of Ukraine, according to M.P. Baida (2025), higher yields of the soybean variety Aratta were obtained with the combined use of YaraVita

Mono Molitrac at the budding stage (0.25 L/ha) and the micronutrient fertiliser Radostym – 2.35 t/ha, as well as in variants combining YaraVita Mono Molitrac at the budding stage (0.25 L/ha) and at the flowering stage (0.25 L/ha) with growth regulators Biosil and Radostym – 2.34 t/ha and 2.35 t/ha, respectively. The yield of the soybean variety Cordoba under these same treatment combinations was 2.40 t/ha, 2.41 t/ha, and 2.45 t/ha, respectively. In the southern part of the Western Forest-Steppe of Ukraine, D.V. Kozyrsky *et al.* (2025) reported that double foliar feeding with the preparation Fulvohumin resulted in a yield increase of 0.18-0.37 t/ha compared to the base fertilisation variant $N_{30}P_{60}K_{60}$. Foliar fertilisation with Fulvohumin in combination with fungicidal protection ensured a greater realisation of the productivity potential of soybean varieties than the application of these technological elements separately. Yield increases amounted to 0.35 t/ha for the variety Samorodok, 0.43 and 0.41 t/ha for Rohiznianka and Triada, respectively, and 0.65 t/ha for the variety Azymut.

An important criterion for evaluating the effectiveness of agrotechnologies is not only yield but also the economic feasibility of their application. Under the conditions of the Forest-Steppe of Ukraine, M. Grabovskyi *et al.* (2025) found that the maximum conditional net profit and profitability were achieved in the soybean varieties Amadea and Aurelina in the variant with pre-sowing seed treatment using fungicides containing the active ingredients fipronil, thiophanate-methyl, and pyraclostrobin (2 L/t), along with the application of fungicides pyraclostrobin and epoxiconazole during the growing season. The use of these preparations contributed to a statistically significant increase in soybean yield.

Alongside mineral nutrition, seed inoculation is an important factor in increasing productivity. In the study by Ya.O. Yarovyi (2024), it was shown that, on average over three years, soybean yield increased from 2.50 to 3.03 t/ha with the application of N_{30} and up to 3.19 t/ha with N_{60}. The application of complete mineral fertilisers at rates of $N_{30}P_{30}K_{30}$ increased this value to 3.20 t/ha (by 6%), and $N_{60}P_{60}K_{60}$ to 3.40 t/ha (by 7%) compared to nitrogen-only systems. The use of inoculation contributed to a yield increase of 0.38-0.41 t/ha depending on the experimental variant. In the north-eastern Forest-Steppe of Ukraine, A. Melnyk *et al.* (2022) obtained the highest soybean yield (3.02 t/ha) under the application of calculated fertiliser rates ($N_{30}P_{60}K_{90}$): with foliar fertilisation using Wuxal Microplant + Wuxal Combi Plus + Wuxal Aminoplant, yields reached 3.45 t/ha for the variety Lissabon and 3.22 t/ha for Diadema Podillia, which is 1.24-1.41 t/ha higher compared to the absolute control; with the use of fertilisers Basfoliar 36 Extra + Solu Bor + Basfoliar 6-12-6, the variety Kyoto achieved 3.37 t/ha, which is 1.35 t/ha higher than the absolute control.

MATERIALS AND METHODS

The research was conducted in 2024-2025 at the Training and Production Centre of Bila Tserkva National Agrarian University. Experimental design: Factor A – varieties: 'RGT Salsa' and 'RGT Saidina'. Factor B – pre-sowing seed treatment with fungicides and inoculants. 1. Control: no treatment. 2. Fungicide Maxim XL (1.0 L/t) + Apron XL (0.5 L/t) + inoculant RhizoStart (2.0 kg/t). 3. Fungicide Maxim XL (1.0 L/t) + Apron XL (0.5 L/t) + inoculant BioMAG Soya (3.0 kg/t). 4. Inoculant RhizoStart (2.0 kg/t) + biofungicide Ekostern Trichoderma, SC (1.5 L/t). 5. Inoculant BioMAG Soya (3.0 kg/t) + biofungicide Ekostern Trichoderma, SC (1.5 L/t). Factor C – fungicides and micronutrient fertilisers applied during the growing season. 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69).

The arrangement of treatments in the experiment was systematic and sequential. The total plot area was 70 m^2, with an accounting area of 56 m^2. The experiment was conducted in triplicate. Soybean cultivation practices, apart from the studied factors, followed those generally accepted for the Right-Bank Forest-Steppe of Ukraine. The research was carried out in accordance with the methodological recommendations of V.V. Volkodav (2001). Pre-sowing seed treatment with Maxim XL (1.0 L/t), Apron XL (0.5 L/t), and Ekostern Trichoderma, SC (1.5 L/t) was performed in advance, 5-7 days prior to sowing, while inoculation with RhizoStart (2 kg/t) and BioMAG Soya (3 kg/t) was carried out on the day of sowing, in accordance with the manufacturers' recommendations for product use. Seeds and soybean crops in the control treatments were treated with water. Application of fungicides and micronutrient fertilisers was carried out using a knapsack sprayer, in accordance with the application rates recommended by the manufacturers and the working solution rates at the appropriate growth and development stages of the crop.

Yield assessment of soybean varieties was conducted by plot harvesting, followed by grain cleaning and recalculation to 100% purity and 14% moisture content. Statistical processing of the research results was performed using analysis of variance and correlation–regression analysis with the application software Excel and Statistica 12.0. Clustering of soybean yield data was carried out using the method of J.H. Ward (1963) based on Euclidean distances, which minimises the increase in within-group variance at each stage of cluster merging. This method allows for the formation of compact and clearly separated groups of objects according to similar characteristics, making it particularly effective for the analysis of quantitative agronomic data, including yield. During the study, the requirements of the Convention on Biological Diversity (1992) were observed.

RESULTS

The data in Table 1 showed that for the soybean variety 'RGT Salsa', in the control treatment without seed treatment and foliar application of preparations, grain yield amounted to 1.34 t/ha in 2024 and 2.51 t/ha in 2025, with an average value of 1.92 t/ha. The highest yield in 2024-2025 was obtained in the experimental variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69), reaching 1.82 and 3.13 t/ha, respectively, with an average value of 2.48 t/ha.

***Table 1**. Grain yield of the soybean variety 'RGT Salsa' depending on the applied agrotechnological measures (average for 2024-2025), t/ha*

Pre-sowing seed treatment with fungicides and inoculants (B)	Fungicides and micronutrient fertilisers (C)*	2024	2025	Average
Control	1	1.34	2.51	1.92
	2	1.57	2.82	2.19
	3	1.68	2.96	2.32
	4	1.50	2.75	2.13
	5	1.62	2.92	2.27
Maxim XL + Apron XL + RhizoStart	1	1.45	2.65	2.05
	2	1.69	2.97	2.33
	3	1.80	3.10	2.45
	4	1.62	2.89	2.26
	5	1.75	3.06	2.40
Maxim XL + Apron XL + BioMAG Soya	1	1.48	2.68	2.08
	2	1.70	3.00	2.35
	3	1.82	3.13	2.48
	4	1.64	2.92	2.28
	5	1.76	3.10	2.43
RhizoStart + Ekostern Trichoderma, SC	1	1.43	2.61	2.02
	2	1.68	2.94	2.31
	3	1.77	3.02	2.40
	4	1.59	2.85	2.22
	5	1.72	3.00	2.36
BioMAG Soya + Ekostern Trichoderma, SC	1	1.44	2.64	2.04
	2	1.67	2.95	2.31
	3	1.78	3.06	2.42
	4	1.60	2.93	2.27
	5	1.72	3.07	2.40
$LSD_{0.05}$, t/ha, for	B	0.05	0.07	
	C	0.03	0.05	
	BC	**0.10**	**0.12**	

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51–59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51–59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*

***Source:** compiled by the authors*

When the chemical product Kolosal Pro (0.5 L/ha) was replaced with the biofungicide Fitosporin-M Soya (1.5 L/ha), productivity was lower, amounting to 1.78 t/ha in 2024 and 3.06 t/ha in 2025, with no statistically significant difference between these variants ($LSD_{0.05}$ = 0.10 in 2024 and $LSD_{0.05}$ = 0.12 in 2025). Due to improved weather conditions in 2025, an increase in soybean grain yield was observed, with gains ranging from 0.5 to 1.2 t/ha. For the variety ‘RGT Saidina’, grain yield in 2025 was higher by 80.6-93.1% compared to 2024 (Table 2). On average over the two years, the application of pre-sowing seed treatment with fungicides and inoculants resulted in an increase in productivity of 0.18-0.30 t/ha compared to the control plots. In variants with the use of fungicides and micronutrient fertilisers during the growing season, the yield increase compared to the control ranged from 0.21 to 0.40 t/ha. The maximum yield values (1.84 t/ha in 2024 and 3.39 t/ha in 2025) were observed in the variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). The use of the biofungicide Fitosporin-M Soya (1.5 L/ha) in this scheme led to a slight decrease in soybean productivity, indicating the high effectiveness of biological protection systems.

***Table 2**. Grain yield of the soybean variety ‘RGT Saidina’ depending on the applied agrotechnological measures (average for 2024-2025), t/ha*

Pre-sowing seed treatment with fungicides and inoculants (B)	Fungicides and micronutrient fertilisers (C)	2024	2025	Average
Control	1	1.45	2.72	2.09
	2	1.63	3.04	2.34
	3	1.72	3.16	2.44
	4	1.59	2.99	2.29
	5	1.60	3.09	2.35
Maxim XL + Apron XL + RhizoStart	1	1.57	2.95	2.26
	2	1.79	3.30	2.54
	3	1.88	3.43	2.66
	4	1.74	3.26	2.50
	5	1.84	3.40	2.62
Maxim XL + Apron XL + BioMAG Soya	1	1.64	3.00	2.32
	2	1.82	3.33	2.57
	3	1.93	3.49	2.71
	4	1.77	3.30	2.53
	5	1.86	3.43	2.65
RhizoStart + Ekostern Trichoderma, SC	1	1.52	2.91	1.72
	2	1.76	3.27	2.51
	3	1.84	3.39	2.62
	4	1.71	3.22	2.47
	5	1.83	3.37	2.60
BioMAG Soya + Ekostern Trichoderma, SC	1	1.60	2.96	2.28
	2	1.78	3.29	2.53
	3	1.90	3.43	2.67
	4	1.72	3.27	2.49
	5	1.81	3.39	2.60
$LSD_{0.05}$, t/ha, for	B	0.05	0.07	
	C	0.03	0.05	
	BC	**0.10**	**0.12**	

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*

***Source:** compiled by the authors*

It was established that the average grain yield of the variety 'RGT Saidina' was 2.47 t/ha, whereas for 'RGT Salsa' it was 2.27 t/ha, which is higher by 0.2 t/ha or 9.1% in relative terms. In both varieties, the highest yield indicators were obtained under conditions of combined use of chemical (Maxim XL (1.0 L/t) + Apron XL (0.5 L/t)) or biological fungicidal seed protection and inoculation (BioMAG Soya (3 kg/t)), together with double application during the growing season of the fungicides Kolosal Pro (0.5 L/ha) and Fitosporin-M Soya (1.5 L/ha), and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha). It was determined that the greatest contribution to soybean yield formation is made by the genotype (variety) – 43.1% (Fig. 1). The second most influential factor is Factor C with a share of 17.6%, demonstrating the significant impact of fungicides and micronutrient fertilisers on yield. The influence of Factor B amounts to 15.0%, while the interaction between factors B × C accounts for 8.4%. This indicates that the combined application of seed treatment and foliar use of fungicides and micronutrient fertilisers provides an additional increase in yield. Weather conditions also have a considerable effect on soybean productivity – 8.2%. The growing seasons for soya in 2024 and 2025 differed significantly in terms of precipitation and temperature (Table 3).

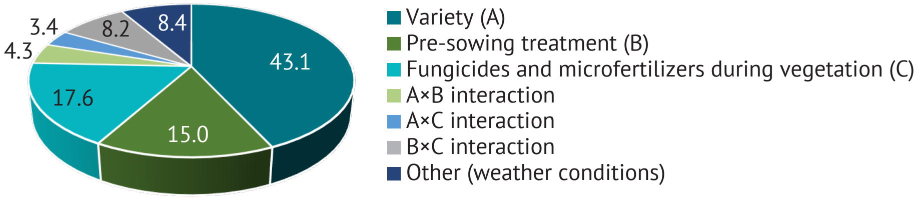


***Figure 1**. Contribution of the factors under study to soyabean yield, %*
***Source:** compiled by the authors*

***Table 3**. Weather conditions during the study years*

Month	Decade	2024		2025	
		Total precipitation, mm	**Average temperature, °C**	**Total precipitation, mm**	**Average temperature, °C**
May	I	0.8	14.8	20.9	12.6
	II	0.1	12.9	2.7	12.5
	III	14.8	19.5	71.5	15.8
	per month	15.7	15.8	95.1	13.6
June	I	21.8	21.3	11.5	21.6
	II	58.8	20	16.0	20.4
	III	0.7	21.2	10.2	21.7
	per month	81.4	20.8	37.7	21.2
July	I	0	22.5	7.8	22.1
	II	40.9	26.5	16.0	24.6
	III	1.2	21.4	31.9	22.0
	per month	42.1	23.5	55.7	22.9
August	I	7.8	20.7	15.9	20.4
	II	1.8	21.2	23.9	21.5
	III	0	23.5	12.5	24.1
	per month	9.6	21.8	52.3	22.0
September	I	3.9	20.8	4.1	19.7
	II	9.3	19.5	18.3	20.4
	III	0	18.2	8.6	16.5
	per month	13.2	19.5	31.0	18.9

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*
***Source:** Crop-monitoring (n.d.)*

In May 2024, dry conditions were observed, with total precipitation of 15.7 mm, whereas in 2025 this indicator amounted to 95.1 mm, providing more favourable conditions for the initial development of soybean plants. June 2024 was better supplied with moisture (81.4 mm) compared to 2025 (37.7 mm). In July 2025, more favourable conditions were observed during the flowering and seed formation period of soybean (55.7 mm of precipitation), along with a more even distribution throughout the month. August 2024 was dry (9.6 mm), which negatively affected the yield potential of soybean, while in 2025 it was, on the contrary, sufficiently supplied with moisture (52.3 mm). The total precipitation in 2024 for the May-September period amounted to 162.0 mm, with an average air temperature of 20.3°C, whereas in 2025 it was 271.8 mm and 19.7°C, respectively. Overall, 2025 was characterised by more favourable conditions for the growth and development of soybean plants, while 2024 was characterised as a stressful year, particularly during critical periods – May and August. To quantitatively assess the influence of weather factors on soybean yield formation, predictive models were developed. Figure 2 presents a comparison of the actual soybean seed yield in 2024 and 2025 with the calculated values obtained based on models that take into account the weather conditions of July and August.

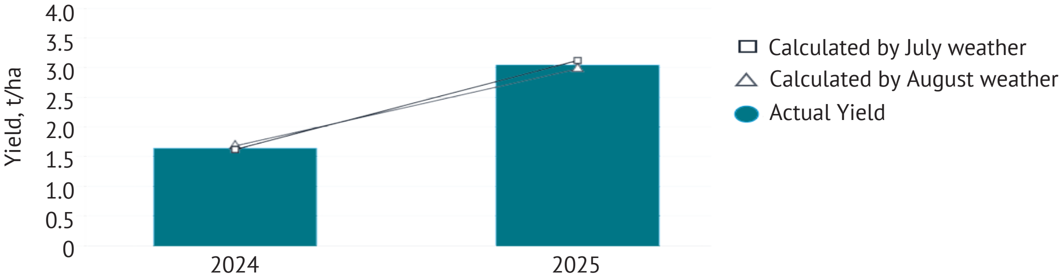


***Figure 2**. Actual and model-calculated soybean seed yield figures, tonnes per hectare*

***Source:** compiled by the authors*

The actual yield in 2024 amounted to 1.68 t/ha, and in 2025 – 3.06 t/ha, indicating a significant increase in productivity due to more favourable weather conditions. Models developed on the basis of weather factors of individual months demonstrated high forecasting accuracy. In 2024, the July model (1.62 t/ha) closely matched the actual data, confirming the decisive role of conditions during the soybean developmental stages (BBCH 51-69) in shaping future productivity. In 2025, the July model slightly overestimated the yield (3.12 t/ha). In 2024, the August model showed a higher value (1.75 t/ha) than the actual yield, indicating that the extreme drought in August (only 1.8 mm of precipitation in the second ten-day period) acted as a limiting factor that the model could not fully account for. In 2025, the August model (2.98 t/ha) was lower than the actual yield. The deviations between actual and calculated values were insignificant (up to 0.07 t/ha), which confirms the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. The July model is more stable for predicting the overall trend in soybean yield, as it is during this period that the structure of the future yield is formed.

In addition to analysing the influence of weather factors, cluster analysis was applied to generalise the obtained results and identify similarities between experimental variants. Figure 3, which presents the results of cluster analysis of the average soybean yield for 2024-2025, clearly shows several hierarchically formed clusters. Clustering was performed using the method of J.H. Ward (1963) with Euclidean distances, allowing the degree of similarity between variants to be assessed based on yield level. The first large cluster includes variants with the highest yield values: 13, 30, 45, 46, 49, and 50. This indicates that, regardless of the variety, certain agrotechnological measures (pre-sowing seed treatment and inoculation, as well as foliar application of fungicides and micronutrient fertilisers) contributed to consistently high yield results in both years of the study. The internal structure of this cluster is quite compact, indicating a high degree of similarity among the variants included in it. The second cluster consists of variants that demonstrated medium yield levels. Within this group, greater variability between variants is observed; however, they form a distinct branch separated from both high- and low-productivity combinations. Variants within this cluster are grouped at smaller Euclidean distances, indicating relatively similar, although not maximum, characteristics.

The third cluster comprises the variants with the lowest yield values: 1, 4, 15, 16, 35, 41. Variant 41 has one of the lowest average yields (1.66 t/ha) and forms its own isolated sub-cluster, showing the greatest distance from the other variants, which may indicate the influence of adverse weather conditions in this trial. Overall, the dendrogram confirms that soyabean yield depends to a significant extent not only on the variety but also on the combination of agronomic practices. Despite the differences between varieties, some experimental variants had similar productivity and are grouped into common clusters, indicating the possibility of optimising cultivation technologies for different genotypes.

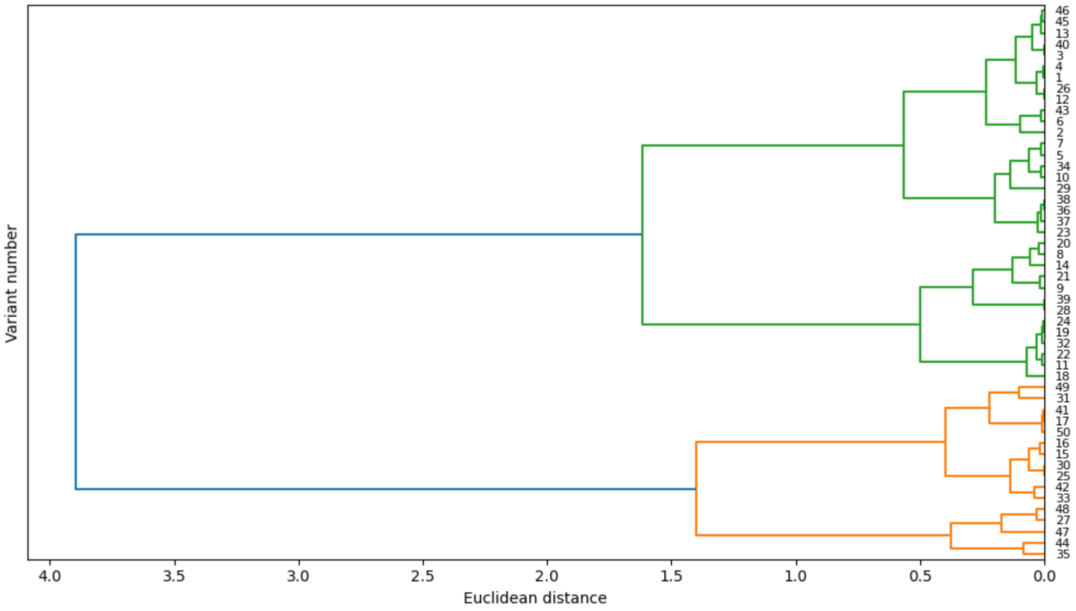


Figure 3. *Dendrogram of cluster analysis of yield of soybean varieties 'RGT Salsa' and 'RGT Saidina' for 2024-2025*
Source: *compiled by the authors*

DISCUSSION

The obtained research results are consistent with data from other authors regarding the influence of climatic factors on crop yields. According to E. Vogel *et al*. (2019), climate extremes increase yield variability of agricultural crops by 18-43%, accounting for more than half of the variance for maize, soybean, and rice. Temperature extremes have a stronger relationship with yield changes than precipitation-related variables such as drought or heavy rainfall. H. Zhang *et al.* (2019) indicated that for every 1°C increase in growing season temperature, soybean yield decreases by 3.1%. Soybean plants are particularly sensitive to elevated temperatures during the reproductive stage, especially during flowering and grain filling. According to H.A. Araji *et al.* (2018), water stress caused by reduced precipitation affects the physiological development of soybean plants and yield formation. As reported by K. Jumrani & V.S. Bhatia (2018), both temperature and water stress influence soybean growth and yield, but the effect is more pronounced when water deficit occurs under high air temperatures.

These findings fully correspond with the results of the present study. In the weather-stressful year of 2024, yields of the soybean varieties 'RGT Salsa' and 'RGT Saidina' ranged from 1.34-1.82 and 1.45-1.93 t/ha, respectively, whereas in the more climatically favourable 2025 (in terms of precipitation and temperature), they reached 2.51-3.13 and 2.72-3.49 t/ha, respectively, which is 70.6-93.1% higher. However, according to results obtained by R. Ramteke *et al.* (2015) in India during 2001-2013, a shift in precipitation from July to August was observed, while soybean yield in Indore district and Madhya Pradesh state increased by 21.6 and 13.9 kg, respectively.

According to the authors' calculations, in 2024 the July model (1.62 t/ha) closely matched the actual soybean yield data, whereas in 2025 the July model slightly overestimated the yield (3.12 t/ha). In 2024, the August model showed a higher value (1.75 t/ha) than the actual yield, while in 2025 the August model (2.98 t/ha) was lower than the actual yield. At the same time, deviations between actual and calculated values were insignificant (up to 0.07 t/ha), indicating the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. These conclusions are also supported by findings of other researchers. According to O. Sobko *et al.* (2020), soybean yield showed a significant positive correlation with solar radiation ($r = 0.32$) and precipitation ($r = 0.33$), but a significant negative correlation with crop heat units (CHU) ($r = -0.42$). M. Tsekhmeistruk *et al.* (2021), based on correlation analysis of weather conditions and soybean yield during 2004-2020, identified a negative effect of average daily temperature in August (correlation coefficient $r = -0.428$). Ya.O. Yarovyi (2024) reported that July precipitation had a positive effect on the crop ($r = 0.501$-0.555). Soybean seed yield varies significantly depending on the weather conditions of the study year, as indicated by a low stability index of 0.36-0.40.

According to Kazakh researchers S. Didorenko *et al.* (2023), the yield of soybean varieties shows a positive correlation with maturity group ($r = 0.87$). Weather conditions had an inconsistent effect on the yield of varieties from different maturity groups. In the driest year, the yield of late-maturing soybean varieties Birlik KV and Zhansaya decreased the most. N.G. Buslaeva *et al.* (2024) established relationships between soybean seed yield and weather elements: a strong correlation with average monthly air temperature was observed for July ($r = -0.931$), while correlations with monthly precipitation were identified for May ($r = -0.875$), June ($r = 0.720$), and August ($r = -0.950$). The strongest combined influence of average daily air temperature and precipitation was found during the third ten-day period of June ($r = -0.938$ and 0.996) and August ($r = 0.976$ and -0.999). Ya.O. Yarovyi (2024) stated that soybean seed yield is most affected by weather conditions and fertilisation, and least by inoculation. Y. He & M.L. Matthews (2023) noted that solar radiation, temperature and relative humidity were the main climatic factors influencing yield improvement, and they showed an inverse correlation with yield improvement during the vegetative phase compared to the reproductive phase of soya.

In addition to the influence of climatic factors, agrotechnological measures, in particular pre-sowing seed treatment and the application of biological products, play an important role in determining soyabean yield. The results of this study showed that pre-sowing treatment of soya bean seeds with fungicides and inoculants contributed to an increase in grain yield of 0.09-0.30 t/ha or 5.1-12.8%, compared to the control. According to S. Hussain *et al.* (2009), soyabean yield in treatments involving seed treatment with the bacterium *B. japonicum* and the fungicide fludioxonil + *B. japonicum* was the highest and significantly exceeded the control treatment by 0.27-0.60 t/ha. Data from S. Kobak *et al.* (2025) indicated that inoculation of soyabean seeds with biological preparations increased yield: 40-45 days before sowing – by 7-10%, 19-21 days before sowing – by 10-16%, and on the day of sowing – by 13-19%. In experiments conducted by Ya.O. Yarovyi (2024), inoculating seeds before sowing yielded 0.54-0.60 t/ha of seeds, compared to plots without fertiliser. Pre-sowing inoculation of soyabeans with a cellular protector was effective 30 days before sowing, and grain yield was similar to that of standard inoculation even under unfavourable environmental conditions, indicating the potential for using this technology even under adverse conditions.

However, researchers A.S.F.D. Araújo & R.S. Araújo (2006) and E.J. Hartley *et al.* (2012) reported on the toxicity of plant protection products used for pre-sowing seed treatment to the bacteria present in inoculants and a possible reduction in yield due to this antagonistic effect. Thus, according to P.P. Pukhtaievych *et al.* (2023), the combined application of inoculants and the Benorad preparation resulted in a reduction in the above-ground biomass of soyabeans by 8.7-20.9% and root biomass by 4.8-16.8% during the growing season, compared with control plants (regardless of the rhizobium strain used for inoculation). A negative effect of seed treatment on the nitrogenase activity of symbiotic systems was noted following the application of Benorad at the three-true-leaf stage and during budding to early flowering.

T. Nyzhnyk *et al.* (2024) found that the application of the inoculant *Bradyrhizobium japonicum* (titre 10^9 cells per ml) and the fungicide fludioxonil (25 g/L) to seeds promoted the development of antioxidant protection in soybean plants under drought conditions through the activation of key enzymatic complexes and regulation of lipid peroxidation processes, which positively affect nitrogen fixation and soybean productivity. This increased the nitrogen-fixing activity of soybean at the pod formation stage by more than 71.7% and also increased soybean yield by 12.7%. Accordingly, in this study no negative effect of fungicides on the growth and development of soybean plants was observed either in the initial period of vegetation or in later stages.

An important element of cultivation technology is also the foliar application of fungicides and micronutrients, the effectiveness of which is confirmed by the obtained results. According to the data, the influence of foliar application of micronutrients and fungicides during soybean vegetation (17.6%) was more significant for yield formation. Thus, grain yield in these variants exceeded the control plots, depending on the variety, by 0.23-0.42 t/ha. This is confirmed by the findings of A.V. Melnyk *et al.* (2019), according to which the use of foliar fertilisation products contributed to an increase in soybean grain yield on average by 0.3-0.5 t/ha, or 12.5-15.5%. Studies by A.V. Holodna *et al.* (2024) showed that plant feeding at the flowering stage with an organo-mineral fertiliser ensured an increase in soybean yield of 0.64 t/ha; the application of the micronutrient YaraVita Mono Molytrac at the budding stage and additionally at the flowering stage with growth regulators increased yield by 0.21-0.44 t/ha. According to D.V. Kozyrsky *et al.* (2025), the fungicide protection system was effective and contributed to the formation of 0.23-0.45 t/ha more soybean grain compared with variants without their application.

Particular attention in modern soybean cultivation technologies is given to the use of biological products as an environmentally safe alternative to chemical plant protection agents. The use of biological products in crop production is highly relevant, and microbiological preparations are increasingly being applied. S.S. Nimenko & M.B. Grabovskyi (2023) and A. Korobko *et al.* (2024) noted that modern biological products contain various microorganisms that can enhance plant resistance to diseases and pests, promote growth and development, and improve the qualitative composition of soil microbiota. According to H. Panda (2017), they are an alternative to mineral fertilisers and pesticides that disrupt natural cycles and negatively affect biota and the environment. L.E. Fuentes-Ramírez & J. Caballero-Mellado (2006) pointed out that the widespread use of biological factors for the intensification of agriculture has not only environmental but, in most cases, economic priority. The positive effect of biofungicides is also confirmed by the data of Y. Prayogo *et al.* (2023) and T.P.C. Ezeorba *et al.* (2023). In this study, the use of the biofungicide Ecostern Trichoderma, SC (1.5 L/t) for pre-sowing seed treatment and the biofungicide Fitosporin-M Soya (1.5 L/ha) during vegetation resulted in lower grain yield than in variants where chemical products were used; however, the difference was not statistically significant, indicating the effectiveness of biological products in soybean cultivation technology.

CONCLUSIONS

According to the results of the two-year study, a significant influence of varietal characteristics, pre-sowing seed treatment and inoculation, as well as foliar application of fungicides and micronutrient fertilisers on soybean yield was established. The highest yield was obtained for the variety 'RGT Saidina' in the experimental variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69) – 2.71 t/ha. The use of the biofungicide Fitosporin-M Soya (1.5 L/ha) within this scheme resulted in a yield of 2.65 t/ha, indicating the high effectiveness of biological preparations. For the variety 'RGT Salsa', yield indicators under these variants were 2.48 and 2.43 t/ha. The variety 'RGT Saidina' provided an average yield of 2.47 t/ha over two years, whereas 'RGT Salsa' yielded 2.27 t/ha, which is higher by 0.2 t/ha or 9.1%.

In 2024, the average soybean yield across the experiment was 1.68 t/ha, while in 2025, under favourable moisture conditions, it increased to 3.06 t/ha. The developed mathematical models confirmed that July data have higher predictive value. Deviations between actual and calculated values were insignificant (up to 0.07 t/ha), indicating the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. Cluster analysis of 50 experimental variants based on soybean grain yield identified three main groups according to productivity level. The first cluster included variants with yields above 2.5 t/ha, most of which combined the use of the inoculant BioMAG Soya with the fungicides Maxim XL (1.0 L/t) + Apron XL (0.5 L/t), as well as the fungicide Kolosal Pro and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active. Further research should be aimed at expanding environmental testing of the experimental variants to assess the stability of the identified relationships under different soil and climatic conditions, as well as at studying the long-term effects of biological preparations on soil microbiota and the efficiency of symbiotic nitrogen fixation in soybean plants. A promising direction is yield modelling using long-term weather datasets to develop adaptive management systems for soybean cultivation under varying climatic conditions.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Araji, H.A., Wayayok, A., Bavani, A.M., Amiri, E., Abdullah, A.F., Daneshian, J., & Teh, C. B.S. (2018). Impacts of climate change on soybean production under different treatments of field experiments considering the uncertainty of general circulation models. *Agricultural Water Management*, 205, 63-71. doi: 10.1016/j.agwat.2018.04.023.

[2] Araújo, A.S.F.D., & Araújo, R.S. (2006). Survival and nodulation of Rhizobium tropici in bean seeds treated with fungicides. *Ciência Rural*, 36(3), 973-976. doi: 10.1590/S0103-84782006000300039.

[3] Bagale, S. (2021). Nutrient management for soybean crops. *International Journal of Agronomy*, 2(10), article number 3304634. doi: 10.1155/2021/3304634.

[4] Baida, M.P. (2025). Yield and quality of soybean varieties depending on cultivation technology elements. *Latest Agricultural Technologies*, 13(2). doi: 10.47414/na.13.2.2025.336247.

[5] Bandara, A.Y., Weerasooriya, D.K., Bradley, C.A., Allen, T.W., & Esker, P.D. (2020). Dissecting the economic impact of soybean diseases in the United States over two decades. *PLoS ONE*, 15(4), article number e0231141. doi: 10.1371/journal.pone.0231141.

[6] Buslaeva, N.G., Golodna, A.V., & Hritsyuk, Ya.V. (2024). Forecasting profitability levels for different soybean (*Glycine max* L.) cultivation technologies. *Agroecological Journal*, 3, 164-172. doi: 10.33730/2077-4893.3.2024.311192.

[7] Chen, X., Wang, L., Niu, Z., Zhang, M., Li, C.A., & Li, J. (2020). The effects of projected climate change and extreme climate on maize and rice in the Yangtze River Basin, China. *Agricultural and Forest Meteorology*, 282-283, article number 107867. doi: 10.1016/j.agrformet.2019.107867.

[8] Convention on Biological Diversity. (1992, June). Retrieved from https://surl.li/nvimfq.

[9] Crop-monitoring. (n.d.). Retrieved from https://crop-monitoring.eos.com.

[10] Didorenko, S., Kabylbekova, G., Kassenov, R., Dalibaeva, A., Andrambayeva, N., & Derbush, S. (2023). Pre-sowing seed treatment of soybean seeds as approach to increase crop yield. *Fundamental and Experimental Biology*, 11128(3), 49-56. doi: 10.31489/2023bmg3/49-56.

[11] Ezeorba, T.P.C., Chukwudozie, K.I., Okoye, C.O., Okeke, E.S., Ezugwu, A.L., & Anaduaka, E.G. (2023). Biofungicides: Classification, applications and limitations. In *Biofungicides: Eco-safety and future trends* (pp. 12-39). Boca Raton: CRC Press.

[12] FAO. (2021). *The impact of disasters and crises on agriculture and food security*. Retrieved from https://www.fao.org.

[13] Fedoruk, I., Bakhmat, O., Khmelianchyshyn, Y., & Gorodyska, O. (2021). Agroecological influence of micronutrient fetilizers and seed inoculation on a soybean crop. *EUREKA: Life Sciences*, 2, 16-24. doi: 10.21303/2504-5695.2021.001747.

[14] Fuentes-Ramirez, L.E., & Caballero-Mellado, J. (2006). Bacterial biofertilizers. In Z.A. Siddiqui (Ed.), *Biocontrol and biofertilization* (pp. 143-172). Dordrecht: Springer.

[15] Getachew, Z., & Abeble, L. (2021). Effect of seed treatment using Mancozeb and Ridomil fungicides on Rhizobium strain performance, nodulation and yield of soybean (*Glycine max* L.). *Journal of Agriculture and Natural Resources*, 4(2), 86-97. doi: 10.3126/janr.v4i2.33674.

[16] Golodna, A.V., Hrytsiuk, Ya.V., Buslaieva, N.G., & Stoliar, O.O. (2024). The impact of fertilization, seed treatment, and meteorological conditions on soybean yield in the Right-Bank Forest-Steppe. *Agriculture and Plant Growing: Theory and Practice*, 2, 58-66. doi: 10.54651/agri.2024.02.07.

[17] Grabovskyi, M., Mostipan, O., Lozinskyi, M., Kozak, L., Fedorenko, E., Ostrenko, M., Gorodetskyi, O., Kachan, L., & Kovalov, D. (2025). Economic and energy efficiency of fungicides and herbicides in soybean crops. *Scientific Papers. Series "Management, Economic Engineering in Agriculture and Rural Development"*, 25(1), 445-453.

[18] Hartley, E.J., Gemell, L.G., & Deaker, R. (2012). Some factors that contribute to poor survival of rhizobia on preinoculated legume seed. *Crop and Pasture Science*, 63(9), 858-865. doi: 10.1071/CP12132.

[19] Hartman, G.L., West, E.D., & Herman, T.K. (2011). Crops that feed the World 2. Soybean – worldwide production, use, and constraints caused by pathogens and pests. *Food Security*, 3, 5-17. doi: 10.1007/s12571-010-0108-x.

[20] He, Y., & Matthews, M.L. (2023). Seasonal climate conditions impact the effectiveness of improving photosynthesis to increase soybean yield. *Field Crops Research*, 296, article number 108907. doi: 10.1016/j.fcr.2023.108907.

[21] Hopper, K.R. (2023). Modeling the effects of plant resistance, herbivore virulence, and parasitism, on the population dynamics of aphids and parasitoids in wheat and soybean in different climates. *Ecological Modelling*, 481, article number 110376. doi: 10.1016/j.ecolmodel.2023.110376.

[22] Hussain, S., Siddique, T., Saleem, M., Arshad, M., & Khalid, A. (2009). Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. *Advances in Agronomy*, 102, 159-200. doi: 10.1016/S0065-2113(09)01005-0.

[23] Jaques, L.B., Coradi, P.C., Rodrigues, H.E., Dubal, Í.T., Padia, C.L., Lima, R.E., & de Souza, G.A.C. (2022). Post-harvesting of soybean seeds – engineering, processes technologies, and seed quality: A review. *International Agrophysics*, 36(2), 59-81. doi: 10.31545/intagr/147422.

[24] Jumrani, K., & Bhatia, V.S. (2018). Impact of combined stress of high temperature and water deficit on growth and seed yield of soybean. *Physiology and Molecular Biology of Plants*, 24(1), 37-50. doi: 10.1007/s12298-017-0480-5.

[25] Kobak, S., Datsko, A., & Chorna, V. (2025). Efficiency of pre-sowing treatment of soybean seeds with bioinoculants at different treatment terms. *Feeds and Feed Production*, 99, 99-111. doi: 10.31073/kormovyrobnytstvo202599-09.

[26] Korobko, A., Kravets, R., Mazur, O., Mazur, O., & Shevchenko, N. (2024). Nitrogen-fixing capacity of soybean varieties depending on seed inoculation and foliar fertilization with biopreparations. *Journal of Ecological Engineering*, 25(4), 23-37. doi: 10.12911/22998993/183497.

[27] Kozyrsky, D.V., Sydorak, I.Ya., Hrygoriev, V.M., Korunyak, O.P., & Trach, I.V. (2025). Formation of soybean productivity depending on microfertilizers and fungicide protection. *Podilian Bulletin: Agriculture, Technology, Economics*, 46, 53-59. doi: 10.37406/2706-9052-2025-1.6.

[28] Mazur, O., Voloshyna, O., Mazur, O., Zayka, K., Dovgopolyi, V., & Yakovets, V. (2025). The effect of seed inoculation and fertilization on the nitrogen fixing capacity of soybean varieties. *Ecological Engineering and Environmental Technology*, 26(5), 82-95. doi: 10.12912/27197050/202888.

[29] Melnyk, A., Romanko, Y., Dudka, A., Brunov, M., Sorokolit, E., & Ruijie, L. (2022). Symbiotic activity and productivity of soybean plants for treatments with growth regulators with anti-stress actio. In *Modern challenges of agrarian transformations in Ukraine: Agriculture, forestry and horticulture* (pp. 68-75). Warsaw: RS Global.

[30] Melnyk, A.V., Romanko, Yu.O., Romanko, A.Yu., & Dudka, A.A. (2019). Influence of weather and climate parameters on the grain yield of modern soybean varieties in the conditions of the North-Eastern Forest-Steppe of Ukraine. *Taurida Scientific Bulletin*, 109(1), 76-83. doi: 10.32851/2226-0099.2019.109-1.12.

[31] Milenko, O., Solomon, Yu., & Veherenko, V. (2022). Impact of agrotechnical factors on soybean yields. *Bulletin of Poltava State Agrarian Academy*, 2, 119-126. doi: 10.31210/visnyk2022.02.14.

[32] Moreira, A., Bonini Neto, A., Bonini, C.D.S.B., Moraes, L.A., & Heinrichs, R. (2023). Prediction of soybean yield cultivated under subtropical conditions using artificial neural networks. *Agronomy Journal*, 115(4), 1981-1991. doi: 10.1002/agj2.21360.

[33] Nadeem, M., Li, J., Yahya, M., Sher, A., Ma, C., Wang, X., & Qiu, L. (2019). Research progress and perspective on drought stress in legumes: A review. *International Journal of Molecular Sciences*, 20(10), article number 2541. doi: 10.3390/ijms20102541.

[34] Nimenko, S.S., & Grabovskyi, M.B. (2023). Grain yield of soybean varieties depending on elements of organic farming technology. *Irrigated Agriculture*, 79, 52-59. doi: 10.32848/0135-2369.2023.79.7.

[35] Nyzhnyk, T., Kots, S., & Pukhtaievych, P. (2024). Rhizobium inoculant and seed-applied fungicide effects improve the drought tolerance of soybean plants as an effective agroecological solution under climate change conditions. *Frontiers in Bioscience-Elite*, 16(3), article number 23. doi: 10.31083/j.fbe1603023.

[36] Panda, H. (2017). *Manufacture of biofertilizer and organic farming*. New Delhi: Asia Pacific Business Press Inc.

[37] Petrychenko, V., Korniychuk, O., Lykhochvor, V., Kobak, S., & Pantsyrev, O. (2024). Study of sowing quality of soybean seeds depending on pre-sowing treatment of seed. *Journal of Ecological Engineering*, 25(7), 332-339. doi: 10.12911/22998993/188932.

[38] Petrychenko, V., Lykhochvor, V.V., & Ivaniuk, S.V. (2016). *Soia*. Vinnytsia: Dilo.

[39] Prayogo, Y., Bayu, M.S.Y.I., Indiati, S.W., Sumartini-Mejaya, M.J., Harnowo, D., Susanto, G.W.A., & Baliadi, Y. (2023). Innovation of main pest and disease control technology using biopesticides on soybean (*Glycine max* L.). *Applied Ecology & Environmental Research*, 21(1), 589-608. doi: 10.15666/aeer/2101_589608.

[40] Prymak, I., Grabovskyi, M., Fedoruk, Yu., Prysiazhniuk, N., Lozinskyi, M., Voitovyk, M., Karaulna, V., Yezerkovska, L., & Pokotylo, I. (2025). Microbiological and enzymatic activity of typical chernozem under different tillage and fertilization systems. *Scientific Papers Series A. Agronomy*, 68(2), 188-197.

[41] Pukhtaievych, P.P., Kukol, K.P., Vorobey, N.A., & Kots, S.Ya. (2023). The effect of bacterization and pre-sowing seed treatment with benorad on the growth of soybean plants and the realization of the symbiotic potential of pesticide resistant rhizobia. *Studia Biologica*, 17(1), 69-79. doi: 10.30970/sbi.1701.705.

[42] Ramteke, R., Gupta, G.K., & Singh, D.V. (2015). Growth and yield responses of soybean to climate change. *Agricultural Research*, 4(3), 319-323. doi: 10.1007/s40003-015-0167-5.

[43] Rathjen, J.R., Ryder, M.H., Riley, I.T., Lai, T.V., & Denton, M.D. (2020). Impact of seed-applied pesticides on rhizobial survival and legume nodulation. *Journal of Applied Microbiology*, 129(2), 389-399. doi: 10.1111/jam.14602.

[44] Setiyono, T.D., Weiss, A., Specht, J., Bastidas, A.M., Cassman, K.G., & Dobermann, A. (2021). Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. *Field Crops Research*, 100(2-3), 257-271. doi: 10.1016/j.fcr.2006.07.011.

[45] Shelke, D.B., Chambhare, M.R., Nikalje, G.C., & Nikam, T.D. (2023). Improvement of soybean crop for yield, stress tolerance, and value-added products using a transgenic approach. *Advances in Agriculture*, 2023(1), article number 8166928. doi: 10.1155/2023/8166928.

[46] Singer, W.M., *et al.* (2023). Soybean genetics, genomics, and breeding for improving nutritional value and reducing antinutritional traits in food and feed. *The Plant Genome*, 16(4), article number e20415. doi: 10.1002/tpg2.20415.

[47] Sobko, O., Stahl, A., Hahn, V., Zikeli, S., Claupein, W., & Gruber, S. (2020). Environmental effects on soybean (*Glycine max* (L.) Merr) production in central and South Germany. *Agronomy*, 10(12), article number 1847. doi: 10.3390/agronomy10121847.

[48] Strom, N., Hu, W., Haarith, D., Chen, S., & Bushley, K. (2020). Interactions between soil properties, fungal communities, the soybean cyst nematode, and crop yield under continuous corn and soybean monoculture. *Applied Soil Ecology*, 147, article number 103388. doi: 10.1016/j.apsoil.2019.103388.

[49] Tsekhmeistruk, M., Pankova, O., Kolomatska, V., Kobyzieva, L., Artiomov, M., & Sirovitskiy, K. (2021). Influence of weather and climatic conditions on soybean yield. *Ukrainian Journal of Ecology*, 11(4), 11-17. doi: 10.15421/2021_193.

[50] Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N., & Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14, article number 054010. doi: 10.1088/1748-9326/ab154b.

[51] Volkodav, V.V. (2001). *Methods of state variety testing of agricultural crops. Issue 3 (oil, industrial, fiber and fodder crops)*. Kyiv: Alefa.

[52] Ward, J.H. (1963). Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*, 58(301), 236-244. doi: 10.1080/01621459.1963.10500845.

[53] Yarovyi, Ya.O. (2024). Soybean productivity depending on fertilization and inoculation. *Collection of Uman National University*, 105(1), 268-278. doi: 10.32848/2415-8240-2024-105-1-268-278.

[54] Zhang, H., Zhou, G., Li Liu, D., Wang, B., Xiao, D., & He, L. (2019). Climate-associated rice yield change in the Northeast China Plain: A simulation analysis based on CMIP5 multi-model ensemble projection. *Science of the Total Environment*, 666, 126-138. doi: 10.1016/j.scitotenv.2019.01.415.

[55] Zhang, J.Q., Zhang, L.X., Zhang, M.H., & Watson, C. (2019). Prediction of soybean growth and development using artificial neural network and statistical models. *Acta Agronomica Sinica*, 35(2), 341-347. doi: 10.1016/S1875-2780(08)60064-4.

Формування врожайності сої залежно від сортових особливостей і агротехнологічних прийомів на основі прогностичного моделювання

Ігор Лабунський
Аспірант
Білоцерківський національний аграрний університет
09117, пл. Соборна, 8/1, м. Біла Церква, Україна
https://orcid.org/0009-0009-3201-4064

Микола Грабовський
Доктор сільськогосподарських наук, професор
Білоцерківський національний аграрний університет
09117, пл. Соборна, 8/1, м. Біла Церква, Україна
https://orcid.org/0000-0002-8494-7896

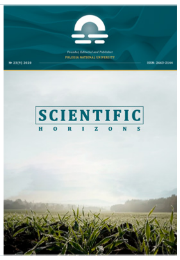
Анотація. У статті висвітлено результати дворічного польового досліду щодо вивчення впливу сортових особливостей, агротехнологічних прийомів та погодних умов на врожайність сої з використанням прогностичного моделювання. Актуальність дослідження обумовлена необхідністю підвищення стабільності врожаю сої в умовах кліматичних змін і важливістю застосування біологічних засобів захисту рослин (біофунгіцидів). Метою було встановлення ефективності різних схем передпосівної обробки насіння та позакореневого застосування фунгіцидів і мікродобрив, а також розроблення математичних моделей прогнозування врожайності сої залежно від погодних умов. Польові дослідження проводилися в 2024-2025 роках на базі Навчально-виробничого центру Білоцерківського національного аграрного університету з сортами сої ‘РЖТ Сальса’ і ‘РЖТ Сайдіна’. Дослід включав 50 варіантів. Встановлено, що найбільшу врожайність (2,71 т/га) отримано у сорту ‘РЖТ Сайдіна’ за комбінованого використання фунгіцидів Максім XL, Апрон XL, інокулянта БіоМАГ Соя і дворазового внесення фунгіциду Колосаль Про з мікродобривами Інтермаг Молібден і Квантум Бор Актив у фазу бутонізації (BBCH 51-59) і фазу цвітіння (BBCH 60-69). За цієї схеми, варіанти з біофунгіцидом Фітоспорин-М Соя забезпечили врожайність 2,65 т/га, що підтверджує високу ефективність біологічного захисту. Математичне моделювання виявило високий рівень відповідності між фактичними і розрахованими даними (похибка до 0,07 т/га). Кластерний аналіз 50 досліджених варіантів за врожайністю зерна сої виявив три основні групи за ступенем продуктивності. До першого кластеру увійшли варіанти з врожайністю понад 2,5 т/га, більшість з яких поєднували застосування інокулянта БіоМАГ Соя з фунгіцидами Максім XL (1,0 л/т) + Апрон XL (0,5 л/т) та фунгіцидом Колосаль Про і мікродобривами Інтермаг Молібден (1,0 л/га) + Квантум Бор Актив. Практична цінність результатів полягає у виділенні оптимальних комбінацій застування біологічних і хімічних фунгіцидів, інокулянтів та мікродобрив для підвищення продуктивності сої, а також у можливості прогнозування врожайності на основі кліматичних показників

Ключові слова: інокуляція; фунгіциди; сорт; мікродобрива; кліматичні умови; кластеризація

ISSN 2663-2144
e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 29(1), 66-78
UDC 636.3;519.85;004.94
DOI: 10.48077/scihor1.2026.66



The influence of agro- and meteorological factors on sunflower yield

Anatolii Kulyk*
PhD in Physics and Mathematics, Head of Department
Kyiv National Economic University named after Vadym Hetman
03057, 54/1 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-6629-0253

Valentyna Lisovska
PhD in Physics and Mathematics, Professor
Kyiv National Economic University named after Vadym Hetman
03057, 54/1 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0001-8675-3975

Olha Melnyk
PhD in Physics and Mathematics, Associate Professor
Kyiv National Economic University named after Vadym Hetman
03057, 54/1 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-4399-176X

Nadiia Shchekan
Senior Lecturer
Kyiv National Economic University named after Vadym Hetman
03057, 54/1 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-1784-6139

Article's History:
Received: 07.11.2025
Revised: 02.03.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. Sunflower is one of the leading oilseed crops in Ukraine, and the stability of its yield is of important economic and food importance. In conditions of increasing climate variability, the need for quantitative analysis of the influence of agrotechnical and meteorological factors on the development of the yield is becoming more urgent. The purpose of the study was to quantitatively assess the role of agrotechnical and climatic factors in the development of sunflower yield using statistical analysis methods. The empirical basis of the study was data for 2007-2024, including sunflower yield indicators, levels of mineral and organic fertilisers, and meteorological characteristics (soil temperature in May, precipitation, air moisture saturation deficit, Selyaninov hydrothermal coefficient, wind speed, number of clear days during the growing season). The study used descriptive statistics, the Shapiro-Wilk test, Pearson and Spearman correlation analysis, and multivariate linear regression. The results of the study showed that the average yield level for the period was 25.65 q/ha with a standard deviation of 5.91 q/ha. The most stable and statistically significant effect on sunflower yield was the level of mineral fertiliser application, for which a moderately strong positive relationship was recorded ($r = 0.656$). Among meteorological factors, the most noticeable positive relationship was found for wind speed ($r = 0.512$). The

Suggested Citation:
Kulyk, A., Lisovska, V., Melnyk, O., & Shchekan, N. (2025). The influence of agro- and meteorological factors on sunflower yield. *Scientific Horizons*, 29(1), 66-78. doi: 10.48077/scihor1.2026.66.

*Corresponding author

multicollinearity test using the variance inflation coefficient confirmed the correctness of the model, since the values for most variables did not exceed 4, and the maximum indicator was 5.17 for mineral fertilisers. The analysis emphasised the key role of agrotechnical management, since the influence of factors such as Selyaninov hydrothermal coefficient (r = 0.083) and moisture deficit (r = 0.092) turned out to be weak within the paired analysis. The practical value of the results lies in the possibility of using the developed regression models to predict sunflower productivity and optimise mineral nutrition systems in order to minimise risks caused by adverse meteorological factors

Keywords: agrometeorological indicators; Selyaninov hydrothermal coefficient; multicollinearity; correlation analysis; linear regression; variance inflation factor

INTRODUCTION

Sunflower has traditionally occupied the place of one of the leading oilseed crops of Ukraine, acting as a strategic resource for domestic consumption and export potential of the country. Its role as a key component of the world agricultural market has led to special attention of researchers to the stability of yield, since any fluctuations in production volumes had a direct impact on economic security and food stability. In current conditions of climatic instability, there has been an increase in the importance of both agrotechnical and meteorological factors, which together determined the dynamics of yield development and caused interannual variability in crop productivity.

Scientific studies have confirmed the complex nature of yield development under the influence of a complex of factors. In particular, D. Baranskyi (2024) substantiated that the temperature regime and the level of moisture supply acted in close interaction with soil cultivation systems, which determined the final productivity of the crop. In turn, J. Beteri *et al*. (2024) established that dynamic changes in air temperature and precipitation significantly adjusted the suitability of certain periods for the sowing campaign. The researchers also proved that the ecological parameters of the environment determined the limits of the potential yield level that the crop could approach under optimal conditions. Additionally, the study by F. Zabel *et al*. (2025) highlighted the role of solar insolation and mineral nutrition systems as factors that minimised the negative effects of climatic stresses. The importance of weather conditions as the main determinant of interannual yield variation has been extensively analysed in a number of international studies based on multi-year climate series. For example, S. Majumder & C.M. Mason (2025) focused on the analysis of historical data, which allowed them to identify a high predictive potential of temperature indicators precisely during critical phases of sunflower vegetation. Furthermore, C.O. Joseph *et al*. (2025) demonstrated that the amount of precipitation during the growing season was the main limiting factor, explaining up to 60% of yield variability in arid regions. These scientific results indicated the need for deeper integration of agrometeorological trends in the model for estimating future productivity.

Along with natural factors, the scientific community has actively investigated the role of anthropogenic and technological influences. The study by M. Zalai *et al*. (2025) showed that the negative effect of meteorological anomalies could be partially offset by the introduction of precise fertilisation systems. Moreover, E. Partal (2022) emphasised that the choice of tillage method directly modified the impact of precipitation on the water regime, creating a complex system of interaction between the agronomist's management decisions and the forces of nature. Thus, crop formation was considered not as a linear process, but as the result of the synergy of many variables. For the agricultural sector of Ukraine, this issue has become particularly acute. S.M. Shakalii & Ye.I. Kulyk (2025) stated in their study that the agroclimatic conditions of the last decade were characterised by a steady trend towards an increase in average annual temperatures and a shift in the zones of comfortable cultivation of oilseeds.

In view of the above, there was an objective need to conduct a comprehensive quantitative analysis of the impact of agrotechnical and meteorological factors on sunflower yield. The use of advanced statistical and econometric tools allowed considering the problem of multicollinearity of indicators, which previously often became an obstacle to obtaining reliable models. The use of distribution testing methods and regression analysis provided the opportunity not only to identify the most influential factors, but also to assess the degree of their contribution to the overall result. The purpose of this study was to assess the impact of agrotechnical and meteorological factors on sunflower yield based on statistical analysis of empirical data over a long period.

LITERATURE REVIEW

Based on the analysis of the current state of the agricultural market, I.V. Chekhova (2022) highlighted the specifics of the functioning of the oilseed market in Ukraine, argued the need to improve the state agrarian policy to support the diversification of production, expand the range of products, and stimulate producers to grow various oilseeds. The study by O.V. Sydiakina & V.V. Hamajunova (2023) was devoted to the analysis of the current state and prospects of sunflower seed production. The researchers considered the key factors affecting the efficiency of seed production and outline the areas of development of the industry based on contemporary scientific and practical achievements. K. Vasylkovska *et al.* (2022) investigated the dynamics of sunflower production in Ukraine and the world for the period 2000-2021 in the context of global climate change. The study emphasised that due to the adaptation of technologies and the selection of drought-resistant hybrids, the average yield in Ukraine increased by 2.5 times, which allowed the country to remain the world leader in sunflower oil exports despite adverse climatic challenges.

P. Debaeke *et al.* (2023) developed and evaluated methods for predicting sunflower yields at the field level using a combination of remote sensing (satellite imagery) and statistical modelling. The paper by K. Amankulova *et al.* (2023) explored methods for accurately estimating future sunflower yields. The researchers used remote sensing data to analyse vegetation indices in combination with phenological phases of plant development, which allowed creating reliable statistical models for predicting agricultural land productivity. The study by Z. Song *et al.* (2023) was devoted to the development of a method for automatic recognition of sunflower growth phases using deep learning technologies and multispectral images from unmanned aerial vehicles. The results of the study, tested on multi-year data, demonstrated the high efficiency of the approach for the needs of precision agriculture, providing farmers with operational information for making crop management decisions.

The study by V. Hnatiienko & H. Hnatiienko (2024) was devoted to the development of an intelligent system for accurate assessment of future yields within the framework of digital agronomy. The study analysed the methods of machine learning, deep learning, and computer vision applied to the processing of satellite data and other multivariate indicators. R. Karan *et al.* (2024) examined the application of artificial intelligence methods for yield prediction and early detection of oilseed diseases in the agriculture of the state of Tamil Nadu (India). The researchers proposed an AI-based model that combines agronomic, meteorological, and historical data to improve the accuracy of yield predictions and timely detection of plant diseases. It was shown that the use of machine learning can significantly improve the decision-making process of farmers, contribute to increasing productivity, reducing crop losses, and sustainable development of the agricultural sector of the region.

The study by M.A. Jabed & M.A.A. Murad (2024) was devoted to a comprehensive review of modern machine learning and deep learning approaches for crop yield forecasting, with a detailed analysis of the algorithms used, data sources (climatic, soil, remote sensing, etc.) and model performance indicators. The paper by S. Thavareesan *et al.* (2025) investigated the application of various machine learning methods to accurately predict crop yields in South Asian countries using historical data on yields, weather factors (rainfall, temperature) and pesticide use; the researchers compared the performance of regressor models, highlighting the potential of machine learning to support decision-making in agriculture and resource planning.

Recent research in the agricultural sector demonstrated the increasing use of regularisation methods (Lasso, Ridge, Elastic Net) in yield forecasting models and agricultural indicators, which allows improving the generalisation of estimates and reducing the impact of multicollinearity between variables. Z. Qiu (2022) proposed an algorithm for forecasting the gross domestic product of China's agricultural sector based on the Elastic Net method for working with multivariate economic data. The researchers analysed the impact of various macroeconomic and agricultural indicators on the dynamics of agricultural gross domestic product, reduced the problem of multicollinearity between variables, and improved the accuracy of forecasting. N. Acir (2025) applied regularised regression models (Ridge, Lasso, Elastic Net) to develop a model for predicting soil fertility in semi-arid agroecosystems based on limited data.

A review of the literature has shown that significant progress has been made in the application of cutting-edge technologies and methods for predicting the yield of oilseed crops, particularly sunflowers. The researchers were actively using remote sensing, machine learning, and statistical models to more accurately predict yields considering factors such as climate change, agronomic conditions, and technological adaptations. However, issues such as multicollinearity among variables and data limitations still restrict the accuracy of forecasts. Thus, this literature review demonstrates the importance of further improving yield forecasting methods for effective agricultural production management.

MATERIALS AND METHODS

The object of the study was the processes of sunflower yield development within the Vinnytsia Oblast, Ukraine. The choice of this region as a geographical coverage was conditioned by its key role in the agricultural sector of the state and its location in the Forest-Steppe zone, which was the most representative for analysing the impact of climate change on oilseed crops. Vinnytsia Oblast was characterised by a transition from sufficient to risky moisture, which enabled the most complete assessment of the sensitivity of modern sunflower hybrids to fluctuations in hydrothermal indicators. The empirical basis of the study was annual statistical and meteorological data for the period 2007-2024. The initial boundary of the study (2007) was determined by the availability and integrity of data, and it was from this year that a full array of open data was available.

Paired linear regression was used to analyse the relationship between sunflower yield and individual agro- and meteorological factors, which allowed assessing the area and strength of the influence of each explanatory variable separately. The research data on agro-factors was obtained from the website of the Main Department of Statistics in Vinnytsia Oblast of Ukraine (State Statistics Service of Ukraine, n.d.), and about meteorological factors – from the Sectoral State Archive of Hydrometeorological Observation Materials of the State Emergency Service of Ukraine (n.d.) for the period 2007-2024 and covered each year of the study in the interval from May to September (tables of meteorological observations are not publicly available). The covered 18-year cycle provided the necessary climatic variability, including a representative sample of weather extremes (droughts, temperature anomalies), which was important for high-quality modelling of the crop response to external stimuli. From a statistical standpoint, such a sample size ($n = 18$) was sufficient to confirm the normality of the distribution of variables according to the Shapiro-Wilk criterion and ensure high reliability of the obtained correlation and regression coefficients.

In this study, eight independent variables were used to model sunflower yield, covering both agronomic and meteorological factors. Agronomic factors included the amount of applied mineral and organic fertilisers in kg/ha, which were direct indicators of the level of agrotechnical support of crops and significantly affected the stability and development of plants, contributing to an increase in yield under the conditions of their balanced application. Meteorological factors included: soil surface temperature in May (soil_5), since thermal dynamics determine the rate of crop development and the passage of vegetation phases; average wind speed (wind), which can affect transpiration, moisture evaporation, and the spread of diseases and pollen; air moisture saturation deficit (saturation_deficit), which characterised atmospheric dryness and affects the water balance of plants; the total number of clear days (clear_days), which reflected the solar insolation necessary for photosynthesis; and the hydrothermal coefficient (HTC), which generally characterised the ratio of heat and moisture and was a critical indicator of the favourableness of meteorological conditions for crop growth and development. The choice of these indicators was substantiated by their key role in shaping sunflower yield. The involvement of both agro- and meteorological factors provided a comprehensive approach to yield forecasting, as it considered both controllable (technological) and uncontrollable (natural) components of agricultural production.

The months of May, June, July, August, and September were chosen for meteorological observations, as they were the most representative of the growing season of sunflower. During this period, weather conditions had the maximum impact on the growth, development and yield of the crop. One of the key meteorological indicators included in the analysis was the HTC, which was used to assess the moisture content of an area during the growing season of agricultural crops. HTC was calculated using the Selyaninov equation:

$$\mathrm{HTC} = \frac{10\cdot\sum P}{\sum T}, \tag{1}$$

where $\sum P$ – the sum of precipitation (mm) for the period when the average daily temperature exceeds +10°C, and $\sum T$ – the sum of average daily air temperatures (°C) for the same period.

The Selininov HTC reflects the complex influence of precipitation and temperature on soil water balance and crop development. The normality of the distribution of the studied variables was checked using the S.S. Shapiro & M.B. Wilk (1965) test and QQ-plots (Hu & Yu, 2016). The Shapiro-Wilk test determined the W statistic by the equation:

$$W = \frac{\left(\sum a_i x_{(i)}\right)^2}{\sum (x_i-\bar{x})^2}, \tag{2}$$

where $x_{(i)}$ – observations ordered in ascending order, x_i – variable value, $\bar{x}$ – average value, a_i – coefficients calculated based on the covariances of the normal distribution.

The p-value for a test determined the probability of observing this or a more extreme W-statistic, assuming the data were normally distributed. If the $p\text{-value} > 0.05$, the null hypothesis of normality was not rejected. For all indicators, the p-value exceeded the significance level of 0.05, which formally allowed the use of parametric analysis methods, in particular the Pearson correlation coefficient:

$$r_{xy} = \frac{\sum (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum (x_i-\bar{x})^2 \sum (y_i-\bar{y})^2}}, \tag{3}$$

where x_i and y_i – observations for variables X and Y, $\bar{x}$ and $\bar{y}$ – their average values.

Furthermore, given the small sample size ($n = 18$) and possible marginal effects, to increase the stability of the results, the Spearman correlation coefficient was additionally used, which was calculated using the ranks of the variables:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}, \tag{4}$$

where $d_i = R(x_i) - R(y_i)$ – difference in the ranks of observations for each pair of variables.

Comparison of the results obtained using both coefficients allowed assessing the reliability of the identified relationships between sunflower yield and agro- and meteorological factors. To quantitatively assess the impact of agro- and meteorological factors on sunflower yield, a classical linear regression model was used:

$$\hat{y} = \beta_0 + \sum_i \beta_i x_i, \tag{5}$$

where $\hat{y}$ – predicted yield, β_0 – free term, β_i – coefficients for traits, x_i – values of independent variables (agro- and meteorological factors).

The feasibility of using classical linear regression was substantiated by the results of multicollinearity analysis using the variance inflation factor (VIF) (O'Brien, 2007). For each explanatory variable X_i VIF was calculated using the equation:

$$\mathrm{VIF}_i = \frac{1}{1-R_i^2}, \tag{6}$$

where R_i^2 – coefficient of determination when regressing a variable X_i on all other variables.

All calculations and visualisations were performed using Jupyter Notebook (Python 3). A significance level of $p < 0.05$ was used throughout the study.

RESULTS AND DISCUSSION

The trends in sunflower yield in the Vinnytsia Oblast from 2007 to 2024 were examined. Figure 1 shows a generally upward but unstable dynamics of sunflower yield in Vinnytsia Oblast in 2007-2024. In 2007-2012, the yield was relatively low and fluctuated within approximately 14-22 q/ha, which may indicate less intensive cultivation technologies and higher dependence on weather conditions. Starting from 2013, there has been a sharp increase in yield (over 30 q/ha), after which a period of increased but variable values was established. In 2013-2019, the yield was mainly maintained at the level of 27-34 q/ha with a maximum around 2019, which may be a result of a combination of favourable meteorological conditions, the use of advanced hybrids and optimisation of the fertiliser system. However, noticeable decreases in yield were recorded in 2020 and 2022, which were likely associated with adverse weather conditions or stress factors in agricultural production. In 2023-2024, a partial recovery of yield was observed, but the level remains lower than the peak values of the previous period, which emphasised the high sensitivity of the crop to agro- and meteorological factors. In general, the dynamics indicate a long-term increase in sunflower productivity in the region with significant fluctuations, which justifies the feasibility of quantitative analysis of the impact of agrotechnical and climatic factors on yield.

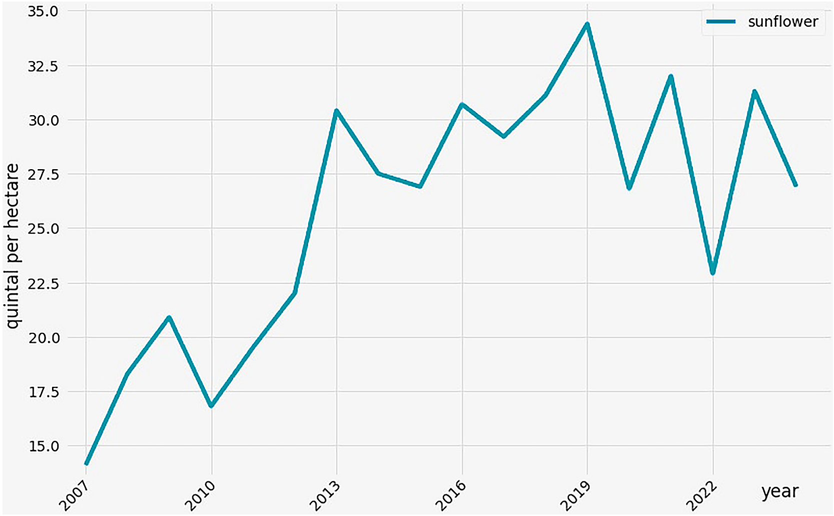


***Figure 1**. Dynamics of changes in sunflower yield in Vinnytsia Oblast from 2007 to 2024*
***Source:** compiled by the authors based on State Statistics Service of Ukraine (n.d.)*

The data in Table 1 were consistent with the graph of sunflower yield dynamics in Vinnytsia Oblast for 2007-2024. The average yield level is 25.65 q/ha, which corresponds to the predominance of values in the range of 25-30 q/ha on the graph in the second half of the period under study. The standard deviation of 5.91 q/ha indicates moderate annual fluctuations in yield, which are clearly manifested in the form of separate sharp declines and rises of the curve (in particular, a minimum of 14.1 q/ha at the beginning of the period and a maximum of 34.4 q/ha in 2019). The negative value of the asymmetry coefficient (Skew = -0.47) indicates a weak left-sided asymmetry of the distribution. The negative coefficient of kurtosis (Kurtosis = -0.88) reflects the absence of sharply expressed peak values and confirms the uniform nature of yield fluctuations. Table 1 presented statistical characteristics of sunflower yield.

***Table 1**. Statistical characteristics of sunflower yield, q/ha*

Metrics	Mean	Std.	Min.	Max.	Skew.	Kurt.
Yield	25.65	5.91	14.1	34.4	-0.47	-0.88

***Source:** compiled by the authors*

Thus, descriptive statistics and the shape of the time series indicate the absence of extreme outliers and the relatively stable nature of yield variation in the period under study. In order to correctly select further statistical methods of analysis, the assumption of normality of the distribution of the studied indicators was additionally checked. Table 2 showed the results of testing the normality of the distribution of variables using the Shapiro-Wilk criterion for agro- and meteorological factors.

***Table 2**. Shapiro-Wilk normality test results for yield, agro- and meteorological variables*

Variable	W_statistic	p_value
yield	0.942	0.312
mineral	0.942	0.310
organic	0.950	0.418
soil_5	0.915	0.106
saturation_deficit	0.948	0.393
HTC	0.952	0.458
wind	0.945	0.353
clear_days	0.917	0.117

***Source:** compiled by the authors*

For all variables, the *p-values* exceed the significance level of 0.05, which means there is no statistical reason to reject the null hypothesis of normal distribution. Figure 2 shows QQ-plots of the assessment of the normality of the distribution of the research variables.

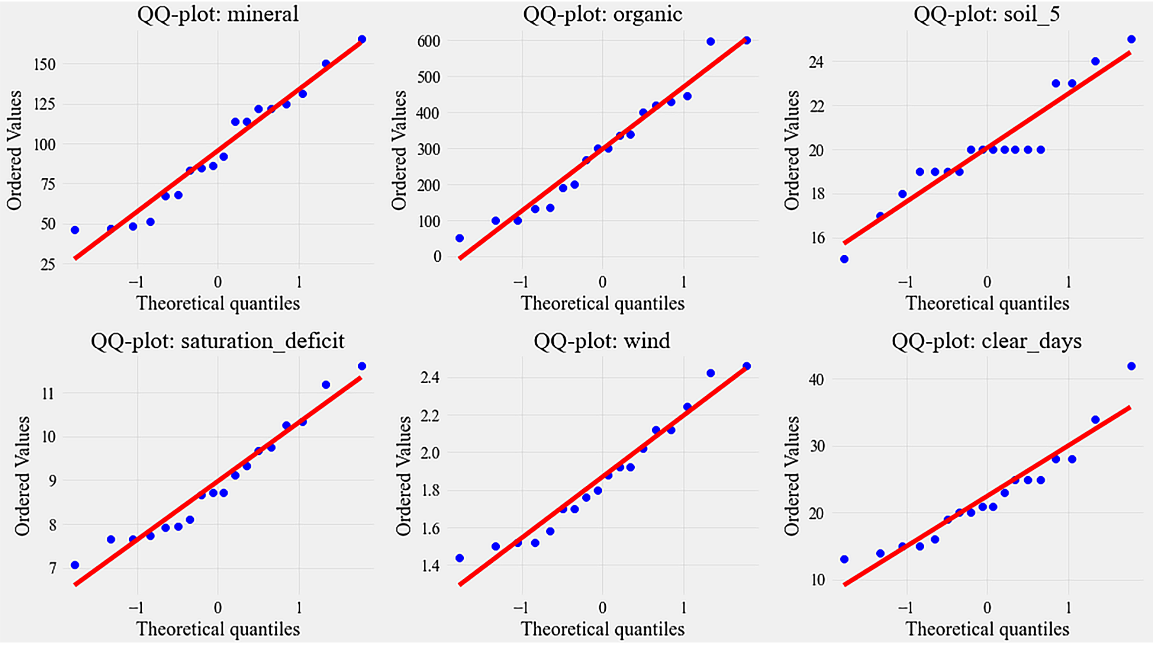


***Figure 2**. Visual assessment of the normality of the distribution of agro- and meteorological factors using QQ-plot*
***Source:** compiled by the authors*

The presented QQ-plots for agro- and meteorological variables allow visually assessing the correspondence of their empirical distributions to the theoretical normal distribution and logically complement the results of the Shapiro-Wilk test. QQ-plots for the variables mineral, organic, soil_5, saturation_deficit, wind, and clear_days generally demonstrated a linear arrangement of points without significant systematic deviations from the theoretical straight line. Minor deviations at the extreme quantiles, in particular for meteorological factors, may be conditioned by the small sample size (n = 18) and variability of weather conditions. Simultaneously, the central parts of the distributions are in good agreement with the normal law, which confirms the acceptability of the assumption of normality and the possibility of using parametric methods of analysis.

Considering the results of checking the normality of the distribution of variables and visual analysis of QQ graphs, to further assess the relationship between sunflower yield and agro- and meteorological factors, correlation analysis was applied using both the Pearson coefficient and the Spearman coefficient, which allows comparing linear and rank dependencies between indicators. Table 3 displays the values of the Pearson and Spearman correlation coefficients between sunflower yield and agro- and meteorological factors, which allows assessing both linear and monotonic relationships.

***Table 3**. Value of Pearson and Spearman correlation coefficients between sunflower yield and agro- and meteorological factors*

Variable	Pearson	Spearman
mineral	0.656	0.632
organic	0.074	0.102
soil_5	-0.190	-0.068
saturation_deficit	0.092	0.066
HTC	0.083	0.035
wind	0.512	0.569
clear_days	0.081	-0.043

***Source:** compiled by the authors*

The most pronounced and stable relationship with sunflower yield was recorded for mineral fertilisers ($r = 0.656$; $\rho = 0.632$), which indicates a moderately strong positive and predominantly linear dependence. A moderate positive relationship was also observed for the wind indicator ($r = 0.512$; $\rho = 0.569$), and a slightly higher value of the Spearman coefficient indicates a monotonic, but not strictly linear nature of the influence. Other agro- and meteorological factors demonstrated weak or absent pairwise correlations with yield, which indicates their indirect influence or manifestation in interaction with other variables. The weak negative correlation of soil temperature in May does not allow drawing unambiguous conclusions within the framework of the pairwise analysis. In general, the closeness of the values of the Pearson and Spearman coefficients confirmed the absence of significant nonlinearities and justified the feasibility of further multivariate regression analysis. Since pairwise correlation analysis reflects only two-dimensional relationships between indicators and does not consider the possible interdependence of explanatory variables, the next stage of the study was to assess the level of multicollinearity between agro- and meteorological factors. For this, the VIF was used, which helped to identify hidden linear dependencies between regressors and assess the feasibility of their simultaneous inclusion in the multivariate regression model (Table 4).

***Table 4**. Value of the VIF for agro- and meteorological factors*

Variable	VIF
soil_5	1.602
organic	1.784
HTC	2.384
clear_days	2.665
saturation_deficit	3.863
wind	5.08
mineral	5.17

***Source:** compiled by the authors*

The values of the VIF indicate the absence of critical multicollinearity between agro- and meteorological factors. Most variables are characterised by a low or moderate level of interdependence (VIF < 4), which confirms their independent contribution to the model. For wind and mineral fertilisers, the VIF threshold values (≈ 5) were recorded, which indicate moderate multicollinearity, but do not exceed the permissible thresholds, enabling the use the least squares method. The results obtained confirm the correctness of the model specification and the feasibility of using the least squares method, providing the possibility of reliable interpretation of the influence of individual agro- and meteorological factors on sunflower yield. The applied approach preserves the transparency of the model and creates the basis for a well-founded economic and agronomic interpretation of the obtained estimates. The linear regression equation describes the average impact of agro- and meteorological factors on sunflower yield, assuming other variables are fixed:

$$\begin{gathered} \mathit{yield} = 25.65 + 5.13^{*}\text{mineral} - \\ - 0.81^{*}\mathit{organic} + 0.42^{*}\text{soil\_5} - \\ - 0.18^{*}\mathit{saturation\_deficit} - 0.24^{*}\mathit{HTC} - \\ - 0.11^{*}\text{wind} - 1.93^{*}\text{clear\_days}. \end{gathered} \tag{7}$$

Analysis of equation (7) and data in Table 5 identified key patterns in the development of crop productivity. The most statistically significant positive contribution to yield was made by the application of mineral fertilisers (p = 0.03), where an increase in the rate of fertilisers per unit lead to an increase in yield by 5.13 q/ha. This confirmed the critical role of nutrition intensification as the main factor in stabilising production.

***Table 5**. Statistical parameters of the multiple linear regression model*

Coefficient	Value	Standard error	p-value
mineral	5.134	2.811	0.031
organic	0.810	1.651	0.354
soil_5	0.422	1.560	0.084
saturation_deficit	-0.183	2.433	0.413
HTC	-0.243	1.910	0.144
wind	-0.115	2.785	0.024
clear_days	-1.932	2.014	0.361

***Note:** coefficient of determination R^2 = 0.683*
***Source:** compiled by the authors*

High statistical significance was demonstrated by the indicator (p = 0.02). The negative coefficient for this parameter indicates the depressive effect of excessive wind activity, which may be associated with increased transpiration and the risks of crop drying in critical phases. The positive coefficient of soil temperature in May (p = 0.08) at the level of statistical trend confirms the importance of the thermal regime for the emergence of seedlings and the formation of the root system. Negative coefficients for moisture deficit, HTC, and number of clear days reflect the complex nature of plant response to hydrothermal stresses. In particular, the negative impact of a large number of clear days may indicate the risks of temperature stress and excessive solar insolation. In general, the obtained model with a high degree of probability (R^2 = 0.68) describes the dominant role of agrotechnical factors, which are the main lever of yield management against the background of changing climatic conditions of the region. Figure 3 shows paired scatter plots and linear regression lines between sunflower yield and selected factors. The presented visualisation clearly reflects the nature of the relationship between sunflower yield and individual agro- and meteorological factors and is in good agreement with the results of correlation and regression analyses.

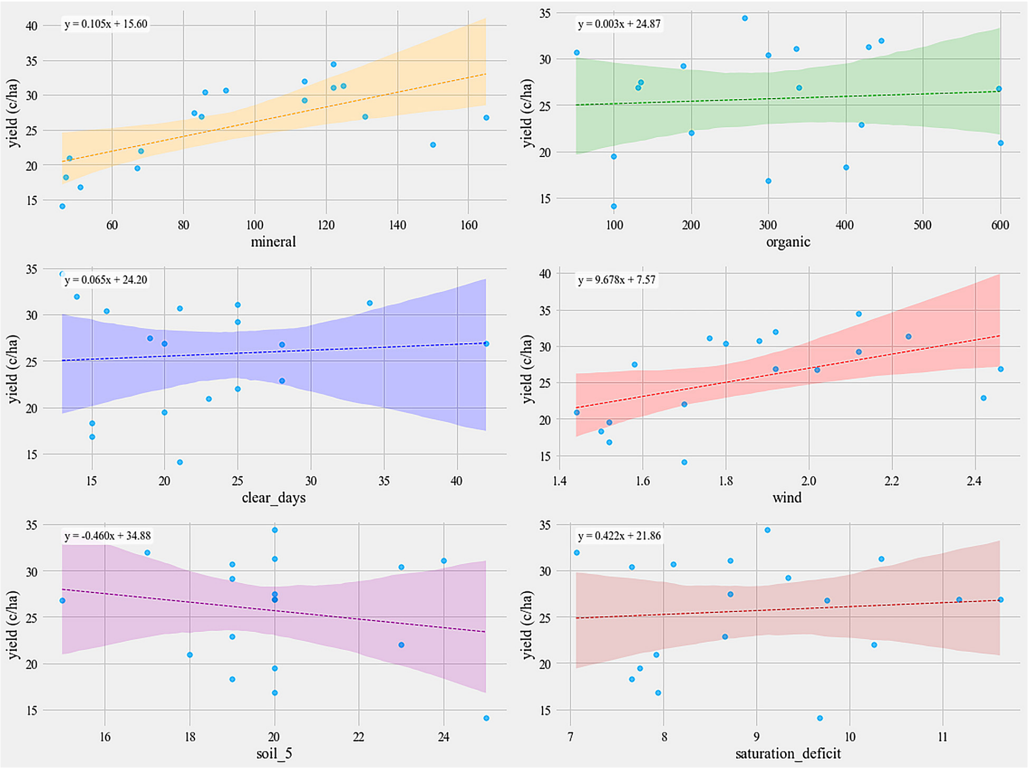


***Figure 3**. Linear relationship between sunflower yield and agro- and meteorological factors (pair analysis)*
***Source:** compiled by the authors*

The most pronounced positive linear dependence was observed for mineral fertilisers: the regression line has a pronounced increasing slope, and the confidence interval was relatively narrow in the central range of values, which indicates a stable and significant impact of this factor on yield. A positive trend is also observed for the wind indicator, but with a greater scatter of points, which indicates a moderate and contextual nature of its impact. The dependence of yield on organic fertilisers and the number of clear days is weak: the regression lines are almost horizontal, and the confidence intervals are wide, which indicates the absence of a clearly pronounced linear effect within the paired analysis. A similar situation was observed for the accumulation deficit, where the variation in yield largely overlaps the possible trend. Soil temperature in May was characterised by a weak negative trend, which may reflect a decrease in yield due to excessive soil warming in the early stages of vegetation, however, the significant scatter of observations does not allow interpreting this effect as dominant.In general, the graphs confirm that mineral nutrition was the main factor with a linear effect on sunflower yield, while meteorological factors mainly modify this effect and manifest themselves weaker or nonlinearly, which justifies the need for multifactorial analysis.

The obtained results of the quantitative analysis of the influence of agro- and meteorological factors on sunflower yield in Vinnytsia Oblast are consistent with contemporary studies on the role of agrotechnical factors under climatic conditions. The most stable and statistically significant positive relationship was found between sunflower yield and the level of mineral fertiliser application, which was confirmed by both correlation analysis ($r = 0.656$, $\rho = 0.632$) and linear regression results. Similar conclusions were obtained in studies by M.J. Mokgolo *et al.* (2024) and M. Furmanets & Y. Furmanets (2025), who showed that adequate mineral nutrition significantly increases sunflower productivity regardless of variations in weather conditions, especially in areas of risky farming. In particular, according to M.J. Mokgolo *et al.* (2024), the combined use of organic and mineral fertilisers increased yield by 38.9%. Furthermore, the weak or statistically insignificant pairwise relationship between yield and organic fertilisers obtained in this study is consistent with the findings E. Partal (2022), who noted the prolonged and contextual nature of their impact, depending on the timing of application, soil conditions, and interaction with other agrotechnical measures. The significant influence of meteorological conditions on sunflower productivity was further confirmed in the multi-year study by F.G. Anton *et al.* (2025), conducted across nine counties of Romania in 2022-2024. The researchers established that the year factor had a statistically highly significant effect on seed yield ($F = 1397.87$, $p < 0.001$). This confirmed that even under conditions of applied agrotechnical measures, extreme heat and moisture deficit during the growing season can critically reduce sunflower yield, which was consistent with the pattern of weak but negative relationship between temperature and yield identified in this study. In the context of projected climate change, the findings of J. Junk *et al.* (2024) were particularly relevant: based on phenological modelling of winter oilseed rape the researchers showed that rising temperatures accelerate crop development and introduce new agroclimatic risks.

Among meteorological factors, the most noticeable positive relationship with yield was demonstrated by average wind speed. Similar results were presented by H. Gürkan (2023) and V. Georgieva *et al.* (2024), who showed that moderate wind regime can contribute to the development of a favourable microclimate for crops. Simultaneously, significant scatter of data indicates the contextual nature of this influence and its dependence on the combination with temperature and hydrothermal conditions. The results obtained regarding meteorological factors are also consistent with the study by J. Beteri *et al.* (2024), who showed a strong positive relationship between precipitation and sunflower productivity for Tanzanian conditions ($r \approx 0.65$ - 0.75) and a negative effect of high temperatures ($r \approx -0.60\ldots-0.77$). These numerical indicators confirmed that it is rain and water supply (similar to the Selyaninov hydrothermal coefficient and moisture deficit) that are more important for the establishment of favourable conditions for sunflower growth, while high temperatures during critical phases of development can have a restraining effect.

Weak pairwise correlations between yield and such indicators as the number of clear days, air moisture saturation deficit, and hydrothermal coefficient do not contradict the literature data. C.O. Joseph *et al.* (2025) emphasised that climatic factors usually affect productivity not in isolation, but through interaction with each other and with agrotechnical factors, which limits the possibilities of pairwise analysis. The results obtained also correspond to the general conclusions regarding the increasing sensitivity of sunflower to climatic fluctuations, given by D. Baranskyi (2024) and F. Zabel *et al.* (2025). Similarly to these studies, the Vinnytsia Oblast is characterised by noticeable interannual fluctuations in yield against the background of a general increase in its average level. Compared to approaches based on machine learning methods (Cvejić *et al.*, 2023; Seck *et al.*, 2025; Nazir *et al.*, 2025), the linear regression used in this research has a lower predictive potential, but provides high interpretability of the results. This allows for clear identification of key influencing factors and is important for agro-economic analysis and practical recommendations.

In general, the results of the study confirmed that sunflower yield is formed under the influence of a complex interaction of agrotechnical and meteorological factors, with mineral nutrition playing a leading role under conditions of increasing climatic variability. Statistical analysis highlighted the critical importance of the hydrothermal regime and wind load, which significantly adjusted crop productivity within the Forest-Steppe zone. It was found that the stabilisation of yields during periods of weather anomalies is achieved mainly by intensification of nutrition systems, which eliminates part of the risks of product shortages. The results obtained emphasise the need to transition to adaptive cultivation technologies that consider not only standard agricultural applications, but also the dynamics of local meteorological indicators.

CONCLUSIONS

The conducted study quantitatively assessed the impact of agrotechnical and agrometeorological factors on sunflower yield in Vinnytsia Oblast for 2007-2024 and established the nature and strength of the relationship between the variables under consideration. The normality test using the Shapiro-Wilk test confirmed the absence of statistically significant deviations from normal distribution for all variables ($p > 0.05$), which justified the use of parametric analysis methods. Multicollinearity analysis using VIF did not reveal any critical violations: VIF values for most variables did not exceed 4, which confirmed the independent contribution of each factor to the model. Correlation analysis revealed that the most stable and statistically significant relationship with yield was characteristic of mineral fertilisers ($r = 0.656$; $\rho = 0.632$), which showed a moderately strong positive linear relationship. A moderate positive relationship was also recorded for the average wind speed indicator ($r = 0.512$; $\rho = 0.569$).

Other meteorological factors – the number of clear days, air humidity deficit, and the Selyaninov hydrothermal coefficient – demonstrated weak or indirect pairwise relationships with yield, which was consistent with the literature data on the predominantly nonlinear and interdependent nature of the influence of climatic factors. The constructed regression model demonstrated high predictive ability, describing 68% of the variability of yield was conditioned by the selected set of factors. Analysis of regression coefficients confirmed the leading role of mineral nutrition ($p = 0.03$): an increase in the rate of mineral fertiliser application per unit was accompanied by a statistically significant increase in crop productivity. A probable negative contribution was recorded for the wind regime indicator ($p = 0.02$): excessive wind activity was associated with a decrease in yield due to increased transpiration and the risks of crop drying out in critical phases of development.

Thus, sunflower yield was developed under the complex influence of controlled agrotechnical and uncontrolled meteorological factors, with the level of mineral nutrition playing a decisive role. The obtained regression equations can be used to predict sunflower productivity and optimise nutrition systems to minimise the risks of climate variability. Prospects for further research are related to expanding the geographical coverage of the sample, including nonlinear and regularised models (Lasso, Ridge, Elastic Net), and analysing interactions between factors to more fully consider the complex nature of crop development in a changing climate.

ACKNOWLEDGEMENTS

The research was carried out as parts of the following R&D project: (0123U101895) Mathematical methods and models in applied economic research.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Acir, N. (2025). Predicting soil fertility in semi-arid agroecosystems using interpretable machine learning models: A sustainable approach for data-sparse regions. *Sustainability*, 17(16), article number 7547. doi: 10.3390/su17167547.

[2] Amankulova, K., Farmonov, N., Mukhtorov, U., & Mucsi, L. (2023). Sunflower crop yield prediction by advanced statistical modeling using satellite-derived vegetation indices and crop phenology. *Geocarto International*, 38(1), article number 2197509. doi: 10.1080/10106049.2023.2197509.

[3] Anton, F.G., Joița-Păcureanu, M., Contescu, L., Cergan, M., Partal, E., & Pintilia, S. (2025). Sunflower production of some genotypes in years 2022, 2023 and 2024, in Romania. *Scientific Papers. Series A. Agronomy*, 68(1), 246-253.

[4] Baranskyi, D. (2024). Managing sunflower growth in the changing climate and fluctuating moisture levels of the Western forest-steppe. *Bulletin of Lviv National Environmental University. Series Agronomy*, 28, 57-66. doi: 10.31734/agronomy2024.28.057.

[5] Beteri, J., Lyimo, J.G., & Msinde, J.V. (2024). The influence of climatic and environmental variables on sunflower planting season suitability in Tanzania. *Scientific Reports*, 14, article number 3906. doi: 10.1038/s41598-023-49581-5.

[6] Chekhova, I.V. (2022). Peculiarities of oilseeds market functioning in Ukraine. *Scientific and Technical Bulletin of the Institute of Oilseed Crops NAAS*, 32, 154-161. doi: 10.36710/IOC-2022-32-15.

[7] Cvejić, S., Hrnjaković, O., Jocković, M., Kupusinac, A., Doroslovački, K., Gvozdenac, S., Jocić, S., & Miladinović, D. (2023). Oil yield prediction for sunflower hybrid selection using different machine learning algorithms. *Scientific Reports*, 13, article number 17611. doi: 10.1038/s41598-023-44999-3.

[8] Debaeke, P., Attia, F., Champolivier, L., Dejoux, J.F., Micheneau, A., Al Bitar, A., & Trépos, R. (2023). Forecasting sunflower grain yield using remote sensing data and statistical models. *European Journal of Agronomy*, 142, article number 126677. doi: 10.1016/j.eja.2022.126677.

[9] Furmanets, M., & Furmanets, Y. (2025). Productivity of sunflower under different tillage and fertilization systems in the Western Forest-Steppe of Ukraine. *Agro-Business Today*. Retrieved from https://agro-business.com.ua/agro/ahronomiia-sohodni/item/31616-produktyvnist-soniashnyku-za-riznykh-system-obrobitku-gruntu-i-udobrennia-v-zakhidnomu-lisostepu-ukrainy.html.

[10] Georgieva, V., Kazandjiev, V., Georgiev, S., Rashev, S., Valkova, D., Mihova, G., Valchev, D., & Dobreva, V. (2024). Agro-climatic conditions for growing of sunflower in different climatic area in Bulgaria. *Scientific Papers. Series A. Agronomy*, 67(2), 224-231.

[11] Gürkan, H. (2023). Evaluation of the impacts of climate change on sunflower with aquacrop model. *Journal of Tekirdag Agricultural Faculty*, 20(4), 933-947. doi: 10.33462/jotaf.1240401.

[12] Hnatiienko, V., & Hnatiienko, H. (2024). Integration of machine learning and deep learning methods for sunflower yield prediction. *Management of Development of Complex Systems*, 59, 225-234. doi: 10.32347/2412-9933.2024.59.225-234.

[13] Hu, Y., & Yu, J.y. (2016). Quantilequantile plot compared with stabilized probability plot in figure on the distribution of the test research. *American Journal of Applied Mathematics*, 4(2), 110-113. doi: 10.11648/j.ajam.20160402.17.

[14] Jabed, M.A., & Murad, M.A.A. (2024). Crop yield prediction in agriculture: A comprehensive review of machine learning and deep learning approaches, with insights for future research and sustainability. *Heliyon*, 10(24), article number e40836. doi: 10.1016/j.heliyon.2024.e40836.

[15] Joseph, C.O., Kambwily, K., & Emmanuel, S.M. (2025). Effects of planting window on grain yield and oil yield under rainfed sunflower (*Helianthus annuus* L.) in Kilwa District, Lindi, Tanzania. *Discover Agriculture*, 3, article number 8. doi: 10.1007/s44279-025-00155-1.

[16] Junk, J., Torres, A., El Jaroudi, M., & Eickermann, M. (2024). Impact of climate change on the phenology of winter oilseed rape (*Brassica napus* L.). *Agriculture*, 14(7), article number 1049. doi: 10.3390/agriculture14071049.

[17] Karan, R., Ramkumar, M.O., & Yokesh, M. (2024). Revolutionizing tamilnadu agriculture: AI-powered crop yield forecasting and disease prediction for oil seed crops. In *2024 1st international conference on cognitive, green and ubiquitous computing* (pp. 1-10). Piscataway: IEEE. doi: 10.1109/IC-CGU58078.2024.10530710.

[18] Majumder, S., & Mason, C.M. (2025). Sunflower yield modeling with explainable artificial intelligence: Historical weather impacts across half a century of American production. *Agronomy Journal*, 117(6), article number e70204. doi: 10.1002/agj2.70204.

[19] Mokgolo, M.J., Zerizghy, M.G., & Mzezewa, J. (2024). Sunflower growth and grain yield under different tillage systems and sources of organic manure on contrasting soil types in Limpopo Province of South Africa. *Agronomy*, 14(4), article number 857. doi: 10.3390/agronomy14040857.

[20] Nazir, A.A., Rubaiat, E., Saiful, I., & Al Sohan, M.F.A. (2025). Evaluating machine learning models for crop yield prediction. In *2025 international conference on quantum photonics, artificial intelligence, and networking* (pp. 1-6). Piscataway: IEEE. doi: 10.1109/QPAIN66474.2025.11171630.

[21] O'Brien, R.M. (2007). A caution regarding rules of thumb for variance inflation factors. *Quality & Quantity,* 41, 673-690. doi: 10.1007/s11135-006-9018-6.

[22] Partal, E. (2022). Sunflower yield and quality under the influence of sowing date, plant population and the hybrid. *Romanian Agricultural Research*, 39, 463-470. doi: 10.59665/rar3944.

[23] Qiu, Z. (2022). An elastic net based algorithm for China agriculture GDP prediction. In *2022 international conference on economics, smart finance and contemporary trade* (pp. 843-849). Paris: Atlantis Press. doi: 10.2991/978-94-6463-052-7_96.

[24] Seck, N.K.G., Ngom, A., Ngom, P., & Noba, K. (2025). Crop yield forecasting in Senegal: Application of machine learning methods. *Discover Agriculture*, 3(1), article number 192. doi: 10.1007/s44279-025-00381-7.

[25] Sectoral State Archive of Hydrometeorological Observation Materials of the State Emergency Service of Ukraine. (n.d.). Retrieved from https://cgo-sreznevskyi.kyiv.ua/uk/struktura-fondiv/21-hda-mhs.

[26] Shakalii, S.M., & Kulyk, Ye.I. (2025). Impact of weather and climatic factors on sunflower seed quality. In *Current directions and challenges in crop production technologies: Proceedings of the 5th international scientific and practical internet conference* (pp. 27-29). Poltava: Poltava State Agrarian University.

[27] Shapiro, S.S., & Wilk, M.B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52(3-4), 591-611. doi: 10.1093/biomet/52.3-4.591.

[28] Song, Z., Wang, P., Zhang, Z., Yang, S., & Ning, J. (2023). Recognition of sunflower growth period based on deep learning from UAV remote sensing images. *Precision Agriculture*, 24, 1417-1438. doi: 10.1007/s11119-023-09996-6.

[29] State Statistics Service of Ukraine. (n.d.). *Main Department of Statistics in Vinnytsia Region*. Retrieved from https://vn.ukrstat.gov.ua/index.php/statistical-information/.

[30] Sydiakina, O.V., & Hamajunova, V.V. (2023). Current state and prospects of sunflower seed production. *Taurida Scientific Herald*, 131, 196-204. doi: 10.32782/2226-0099.2023.131.25.

[31] Thavareesan, S., Sriranganesan, J., & Nishatharan, T. (2025). Exploring machine learning techniques for accurate crop yield prediction. *Annals of Agricultural Science and Technology*, 8(1), 1-7.

[32] Vasylkovska, K., Andriienko, O., Malakhovska, V., & Moroz, O. (2022). Analysis of changes in comfortable sunflower growing areas using the example of Ukraine. *Helia*, 45(77), 175-189. doi: 10.1515/helia-2022-0010.

[33] Zabel, F., Knüttel, M., & Poschlod, B. (2025). CropSuite v1.0 – a comprehensive open-source crop suitability model considering climate variability for climate impact assessment. *Geoscientific Model Development*, 18(4), 1067-1087. doi: 10.5194/gmd-18-1067-2025.

[34] Zalai, M., Bojtor, C., Nagy, J., Széles, A., Monoki, S., & Illés, Á. (2025). Challenges in precision sunflower cultivation: The impact of the agronomic environment on the quality of precision sowing techniques and yield parameters. *AgriEngineering*, 7(5), article number 145. doi: 10.3390/agriengineering7050145.

Вплив агро- і метеофакторів на урожайність соняшника

Анатолій Кулик
Кандидат фізико-математичних наук, завідувач кафедри
Київський національний економічний університет імені Вадима Гетьмана
03057, просп. Берестейський, 54/1, м. Київ, Україна
https://orcid.org/0000-0002-6629-0253

Валентина Лісовська
Кандидат фізико-математичних наук, професор
Київський національний економічний університет імені Вадима Гетьмана
03057, просп. Берестейський, 54/1, м. Київ, Україна
https://orcid.org/0000-0001-8675-3975

Ольга Мельник
Кандидат фізико-математичних наук, доцент
Київський національний економічний університет імені Вадима Гетьмана
03057, просп. Берестейський, 54/1, м. Київ, Україна
https://orcid.org/0000-0002-4399-176X

Надія Щекань
Старший викладач
Київський національний економічний університет імені Вадима Гетьмана
03057, просп. Берестейський, 54/1, м. Київ, Україна
https://orcid.org/0000-0002-1784-6139

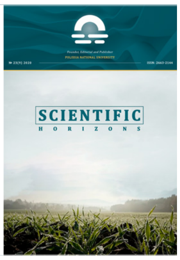
Анотація. Соняшник є однією з провідних олійних культур України, а стабільність його врожайності має важливе економічне та продовольче значення. В умовах посилення кліматичної мінливості актуалізується потреба в кількісному аналізі впливу агротехнічних і метеорологічних факторів на формування врожаю. Метою дослідження була кількісна оцінка ролі агротехнічних і кліматичних чинників у формуванні урожайності соняшника з використанням статистичних методів аналізу. Емпіричну базу дослідження становили дані за 2007-2024 рр., що включали показники урожайності соняшника, рівні внесення мінеральних і органічних добрив, а також метеорологічні характеристики (температура ґрунту у травні, кількість опадів, дефіцит насичення повітря вологою, гідротермічний коефіцієнт Селянінова, швидкість вітру, кількість ясних днів у вегетаційний період). У роботі застосовано описову статистику, критерій Шапіро-Вілка, кореляційний аналіз Пірсона і Спірмена, а також багатофакторну лінійну регресію. Результати дослідження свідчили, що середній рівень урожайності за період становив 25,65 ц/га зі стандартним відхиленням 5,91 ц/га. Найбільш стабільний і статистично значущий вплив на урожайність соняшника мав рівень внесення мінеральних добрив, для якого зафіксовано помірно сильний позитивний зв'язок (r = 0,656). Серед метеофакторів найбільш помітний позитивний зв'язок виявлено для швидкості вітру (r = 0,512). Перевірка на мультиколінеарність за допомогою коефіцієнта інфляції дисперсії підтвердила коректність моделі, оскільки значення для більшості змінних не перевищували 4, а максимальний показник склав 5,17 для мінеральних добрив. Аналіз підкреслив ключову роль агротехнічного управління, оскільки вплив таких факторів, як гідротермічний коефіцієнт Селянінова (r = 0,083) та дефіцит вологи (r = 0,092), виявився слабким у межах парного аналізу. Практична цінність результатів полягає у можливості використання розроблених регресійних моделей для прогнозування продуктивності соняшника та оптимізації систем мінерального живлення з метою мінімізації ризиків, зумовлених несприятливими метеорологічними чинниками

Ключові слова: агрометеорологічні показники; гідротермічний коефіцієнт Селянінова; мультиколінеарність; кореляційний аналіз; лінійна регресія; коефіцієнт інфляції дисперсії

ISSN 2663-2144
e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 29(1), 79-88
UDC 630*22:631.417.1(477)
DOI: 10.48077/scihor1.2026.79



Assessment of the carbon balance of industrial hemp cultivation in Ukraine and its impact on achieving carbon neutrality

Iryna Gruzinska*
Postgraduate Student
Polissya National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0009-0007-6579-316X

Article's History:
Received: 26.09.2025
Revised: 17.02.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. The aim of the study was to determine the climatic potential of industrial hemp as a tool for carbon sequestration and to assess its contribution to achieving carbon neutrality in Ukraine's agricultural sector. The work employed a systematic analysis of contemporary scientific research, an analysis of official statistical data on areas under industrial hemp cultivation, as well as elements of a full life cycle assessment approach to identify emission sources within the cultivation process chain. For the quantitative evaluation of the climatic effect, a computational model of a "digital twin" of a one-hectare hemp field was developed for typical soil and climatic conditions of the Forest-Steppe zone of Ukraine. Based on the modelling of the "digital twin" of the hemp field and the calculated parameters, three carbon sequestration scenarios were established: low, medium and high, reflecting minimum, average and maximum biomass yield levels. It was determined that under the low, medium and high scenarios, the potential absorption amounts to approximately 15.5, 16.5 and 24.75 tonnes of CO_2 per hectare over a single growing season, respectively. At the same time, direct CO_2 emissions from the combustion of diesel fuel used for field operations in the baseline cultivation model were estimated at approximately 0.421 tonnes of CO_2 per hectare, indicating a substantial predominance of sequestration processes over agrotechnological emissions. Under the low scenario, the volume of absorption exceeds direct emissions by approximately 36.8 times; under the medium scenario, by approximately 38 times; and under the high scenario, by 58.8 times. Scenario modelling, developed on the basis of official statistical data on industrial hemp cultivation areas, demonstrated that even with relatively small sown areas, industrial hemp cultivation showed positive dynamics in achieving decarbonisation goals and enhancing the role of agriculture in the national carbon balance. The practical value of the study lies in the possibility of using the obtained results to substantiate carbon farming programmes, integrate industrial hemp into climate policy, and plan the development of processing infrastructure

Keywords: agricultural decarbonisation; sequestration; climate change; biomass; scenario modelling

Suggested Citation:
Gruzinska, I. (2026). Assessment of the carbon balance of industrial hemp cultivation in Ukraine and its impact on achieving carbon neutrality. *Scientific Horizons*, 29(1), 79-88 doi: 10.48077/scihor1.2026.79.

*Corresponding author

INTRODUCTION

Agriculture is increasingly being viewed not only as a source of greenhouse gas emissions, but also as a sector with significant potential for biological carbon sequestration. Industrial hemp, due to its intensive biomass accumulation over a short growing season, is a promising crop for carbon farming systems; however, a quantitative assessment of its net climate impact in the Ukrainian context remains under-researched, although Ukraine is characterised by favourable natural and climatic conditions for growing industrial hemp, particularly in the Polissya and Forest-Steppe zones, where a combination of moderate temperatures, sufficient moisture and fertile soils ensures high crop productivity.

In Ukrainian studies, O.M. Drozd *et al.* (2025) substantiated the feasibility of growing industrial hemp in the Forest-Steppe zone as the region with the most balanced soil and climatic conditions, adaptive crop rotations and suitable agronomic practices. Field experiments by M.V. Roik *et al.* (2024) also confirmed the feasibility of zone-oriented variety selection and optimisation of the mineral nutrition system to achieve stable biomass yields. The dominant direction of research into the environmental efficiency of industrial hemp is the application of a full life-cycle assessment approach and the analysis of the potential 'carbon negativity' of products based on hemp biomass. Such studies focus not only on the biological absorption of carbon dioxide during crop cultivation, but also on the entire value chain – from field to end product. A.T.M.F. Ahmed *et al.* (2022) considered industrial hemp as a promising renewable resource, including its potential use in paper, textiles, composites, biofuels and the food industry.

LCA studies of materials by J.H. Arehart *et al.* (2020) showed that the overall CO_2 balance depends significantly on the business processes accounted for, the method of carbon accounting, and the consideration of carbonisation processes in binding materials. Under certain long-term use scenarios, materials made from industrial hemp can demonstrate a neutral or even negative carbon balance (Nazari & Woods, 2025). The study by M. Michels *et al.* (2025) analysed three aspects that influence the cultivation of industrial hemp: economic, environmental and social. In particular, regarding environmental aspects, it is emphasised that industrial hemp's ability to absorb CO_2 classifies it as a critically important crop for mitigating the effects of climate change. Furthermore, CO_2 sequestration in biomass, as well as the use of industrial hemp in sectors such as construction, further cements this crop's status as "important" for mitigating the effects of climate change, highlighting the need to utilise these plants to create long-term sustainable agricultural systems.

In turn, Z. Shen *et al.* (2022) investigated the potential for carbon sequestration in soil using the example of 100 years of hemp cultivation in France. The study assessed two long-term scenarios for the production of products such as insulation boards for buildings and automotive panels. The production of such products requires the use of hempcrete as a by-product. The study by Z. Shen *et al.* showed that, although additional long-term carbon sequestration in the soil could not be achieved, both scenarios provided long-term climate benefits even beyond 2100, mainly due to carbon sequestration in hemp-based products, as well as the avoidance of fossil fuel-based products.

In the scientific literature, the environmental aspects of industrial hemp cultivation are primarily considered in the context of sustainable agriculture, resource conservation and the reduction of the negative impact of agricultural production on the environment. Indeed, industrial hemp is classified as a crop with high environmental efficiency due to its intensive biomass growth, low requirement for plant protection products, and ability to produce significant amounts of plant biomass over a short growing season without substantially depleting soil resources (Mishchenko & Laiko, 2024). In addition, industrial hemp is considered a bioremediation crop suitable for cultivation on degraded and contaminated land, as it is one of the few plant species capable of reclaiming polluted and abandoned soils.

A study by the Intergovernmental Panel on Climate Change (2019) considered the use of degraded land for industrial hemp cultivation as an effective approach to avoiding competition with food agriculture and minimising the risks of indirect land-use change, which is an important factor in assessing the carbon balance of the agricultural sector. According to the recommendations of the Food and Agriculture Organization of the United Nations (2021), the use of marginal land for growing industrial crops with high biomass accumulation potential allows for a positive climate effect to be achieved even with moderate yields. In turn, there are studies analysing CO_2 emissions from industrial hemp. Thus, the largest contribution of industrial hemp to CO_2 emissions is associated with harvesting, the use of mineral fertilisers and diesel fuel, as well as with energy-intensive post-harvest processing (drying, grinding, pressing) and logistics (Akbarian-Saravi *et al.*, 2025).

Despite the growing number of scientific studies, the issue of quantitatively assessing the net climate effect of industrial hemp cultivation in Ukraine, taking into account both biological carbon sequestration and agronomic emissions, remains under-researched. This study aimed to establish the role of industrial hemp in shaping the carbon balance of agricultural systems and to provide a quantitative justification of its ability to facilitate carbon sequestration in the context of the climate transformation of Ukrainian agriculture.

MATERIALS AND METHODS

The study employed a comprehensive methodological approach combining the synthesis of contemporary scientific research, the processing of official statistics on the scale of industrial hemp cultivation, and the use of elements of life cycle assessment methodology to identify the principal sources of emissions within the production process. Quantitative evaluation of the climatic effect was carried out on the basis of a developed "digital twin" model of a hemp agroecosystem covering 1 hectare, parameterised in accordance with the typical soil and climatic conditions of the Forest-Steppe zone of Ukraine, which accounts for CO_2 absorption during plant growth, carbon accumulation in biomass and soil, and related processes. The methodological foundation of the study also included a systematic analysis of scientific publications by Ukrainian and international authors, regulatory documents of the European Union (EU) in the field of climate policy, and research findings devoted to the environmental characteristics of industrial hemp cultivation and the directions of utilisation of its biomass. The "digital twin" of the hemp field is a conceptual computational model of 1 hectare of industrial hemp crops. The modelling utilised data obtained from the analysis of scientific publications by Ukrainian and international researchers, the author's own calculations, and assumption-based forecasting methods, as presented in Table 1.

The "digital twin" model of a hemp field has been applied to the national statistics on industrial hemp cultivation in Ukraine, shown in Figure 1, in order to determine potential volumes and model possible absorption scenarios in Ukraine.

***Table 1**. Key parameters of the "digital twin" model*

Area of modelling	1 ha
Crop used	*Cannabis sativa* L
Duration of the growing season	120-150 days
Average yield of dry biomass per hectare	8-15 tonnes
Carbon content in dry biomass	45-50%
Average CO_2 absorption per hectare per season	13-25 tonnes
Energy inputs	Diesel fuel for mechanised operations

***Source:** created by the author*

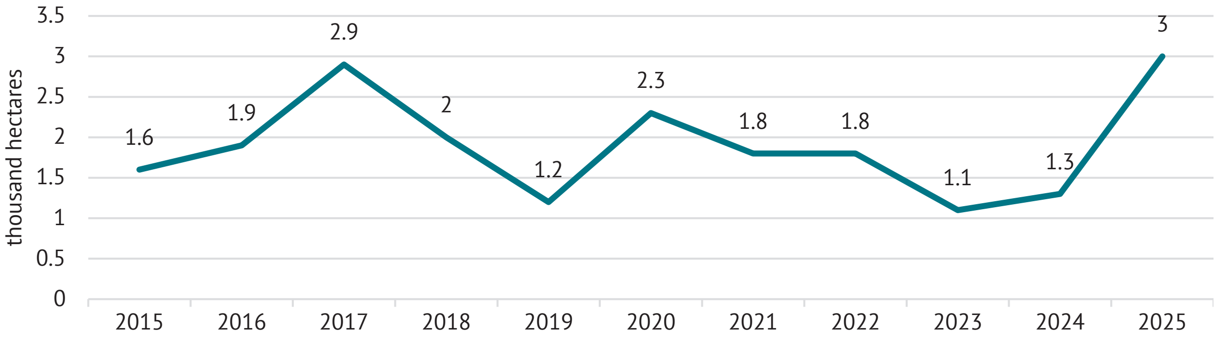


***Figure 1**. Trends in the area under industrial hemp cultivation, 2015-2025, in thousands of hectares*
***Source:** compiled by the author based on data from the State Statistics Service of Ukraine (n.d.)*

The empirical basis for the scenario modelling consisted of official statistical data on the areas sown with industrial hemp in Ukraine. In particular, data from the State Statistics Service of Ukraine (n.d.) were used to calculate the potential volumes of carbon sequestration by industrial hemp at the national level for the period 2020-2025, on the basis of which the dynamics of changes in industrial hemp cultivation areas from 2015 to 2025 were constructed. To estimate the volume of emissions absorption, the results of the study by S.M. Madden *et al.* (2022) on CO_2 absorption by industrial hemp under temperate climate conditions were utilised. According to this study, the level of CO_2 absorption in temperate climates is determined by the duration of the growing season, agronomic practices, and the volume of biomass per hectare, which were taken into account in the parameterisation of the digital twin model. For an accurate assessment of CO_2 absorption, data on dry biomass yield (stems/straw) and the carbon content in the plant mass of *Cannabis sativa* L. were used. In Ukraine, according to the research of H. Laiko (2023), the dry biomass of stems at a minimum level amounts to 8.55-9.81 tonnes per hectare; at a medium level (under average agronomic conditions) – 8-12 tonnes per hectare; and at a high level (in trials with high nutrient supply and optimal conditions) – up to 15 tonnes per hectare. CO_2 absorption is determined on the basis of the stoichiometric relationship between the carbon content in dry biomass and the molar masses of carbon (12) and CO_2 (44). It is assumed that all carbon accumulated in plant biomass originates from atmospheric CO_2. The calculation of absorption was carried out taking into account the carbon fraction in dry biomass using the following formula:

$$\text{absorption indicator (tonnes } CO_2\text{/ha)} = Y(dry) \times 0.45 \times \frac{44}{12}, \qquad (1)$$

where $Y(dry)$ – the yield of dry stem biomass; the coefficient 0.45 represents the carbon content in the dry biomass of industrial hemp stems (45%); and the multiplier $\frac{44}{12}$ – the stoichiometric conversion factor from carbon mass to CO_2 equivalent.

For the analysis of energy inputs in the baseline cultivation model, in particular diesel fuel consumption, it was established on the basis of the author's own calculations and developed technological maps that over the growing season 1 hectare of industrial hemp crops requires approximately 159.9 litres of diesel fuel (Table 2).

***Table 2**. Diesel fuel consumption in the baseline model of industrial hemp cultivation technology, litres per hectare*

Type of work	Quantity, l/ha
Fuel consumption for direct work	117.9
Fuel consumption for indirect work	42.0
Total	159.9

***Note:** direct work – ploughing, sowing, harvesting and other types of land cultivation; indirect work – transporting seeds, workers and other items*
***Source:** created by the author*

Using the method of carbon mass balance under complete combustion, it should be noted that diesel fuel has a density of approximately 0.838 kg per litre and a composition of carbon and hydrogen such that, upon complete oxidation, all carbon is converted into CO_2. The database of the Intergovernmental Panel on Climate Change (2019), which contains emission factors for all types of fuel, including diesel, is based on the assumption that all carbon in the fuel is oxidised to CO_2, and the emission factor for diesel fuel is determined by its calorific value and carbon content, amounting to 2.63 kg CO_2 per litre. The CO_2 formation factor is determined on the basis of combustion stoichiometry:

$$0.838\ \text{kg/L} \times \frac{44}{14} \approx 2.63\ \text{kg } CO_2\text{/L}, \qquad (2)$$

where 44 and 14 – the molar masses of CO_2 and the carbon equivalent of diesel fuel, respectively.

This approach is widely used in scientific research and national reporting, as the amount of CO_2 produced is directly proportional to the amount of fuel burned and its physicochemical characteristics.

RESULTS AND DISCUSSION

Achieving climate neutrality is one of the key challenges facing contemporary global environmental policy. The European Green Deal sets the target of reducing greenhouse gas emissions by at least 55% by 2030 and establishing a climate-neutral economy by 2050, as enshrined in the relevant EU strategic and regulatory acts (Regulation (EU) 2021/1119, 2021; European Commission, n.d.b). In this context, agriculture is increasingly viewed not only as a source of emissions, but as a sector with significant potential for biological carbon sequestration and the implementation of nature-based climate solutions. One of the promising crops in this regard is industrial hemp (*Cannabis sativa* L.), the cultivation of which is showing a steady upward trend globally due to the liberalisation of legislation and growing demand for environmentally friendly raw materials. As of 2025, over 70 countries permit the cultivation of industrial hemp, with China, France, Canada and the USA being the largest producers. Furthermore, Australia, New Zealand, Germany, the Netherlands and other countries have active industrial hemp markets that continue to grow (Fig. 2). The cultivation of industrial hemp is gaining momentum in the EU as well, as evidenced by data from the European Commission (n.d.a.), which showed that the area under industrial hemp has increased significantly. The overall trend in the development of this segment of agricultural production between 2004 and 2023 is shown in Figure 3. Thus, cultivation areas are gradually increasing across the EU, with France being the largest producer of industrial hemp in the EU, accounting for around 60% of total production, followed by Germany (17%) and the Netherlands (5%), whilst the remaining market share is accounted for by other Member States (European Commission, n.d.a). A study by J.G. Cortés *et al*. (2024) noted that the rise in demand for industrial hemp in the EU has contributed to a significant increase in the area under cultivation of this plant, rising by 46.5% between 2016 and 2022. This demand is driven not only by the wide range of economic applications for industrial hemp, but also by its environmental benefits, particularly the goal of achieving climate neutrality by 2050. The authors also highlight the industrial use of hemp fibre in the context of the future potential of hemp by-products as alternative agricultural commodities in EU countries. According to estimates by the European

Commission (n.d.a), industrial hemp directly contributes to achieving the goals of the European Green Deal, as one hectare of crops is capable of absorbing between 9 and 15 tonnes of carbon dioxide, which is comparable to the figures for young forest plantations, but over a significantly shorter growth period, namely around five months. This rate of biomass formation leads to industrial hemp being considered a promising crop for carbon farming systems and for rapidly offsetting emissions from other sectors of the economy.

***Figure 2**. Map of countries that are active producers of industrial hemp*
***Source:** compiled by the author based on research of Hemp CBD Business Plans (2026)*

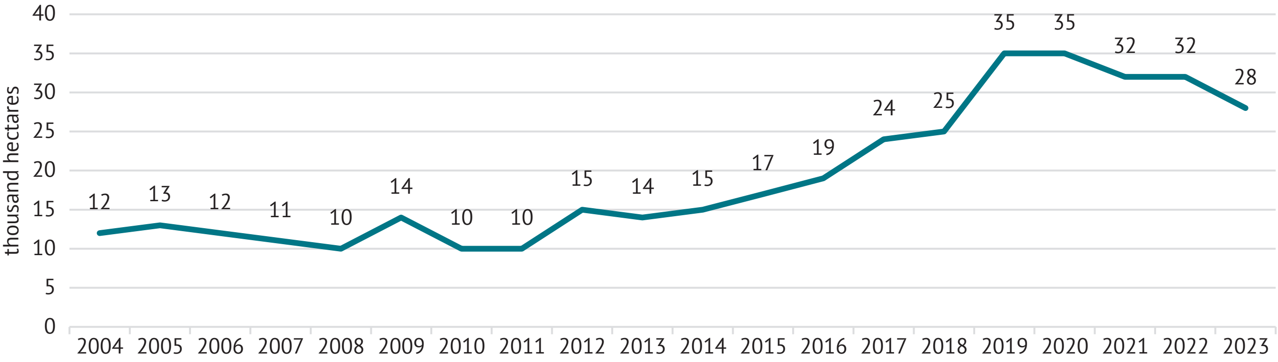


***Figure 3**. Trends in industrial hemp acreage in the EU, 2004-2023, in thousands of hectares*
***Source:** compiled by the author based on research of O. Nykoliuk & K. Sych (2025)*

In Ukraine, the development of industrial hemp cultivation has long been held back by excessive regulatory burdens, with the result that cultivation areas have fluctuated between 2,000 and 4,000 hectares, despite the sector's significant historical potential. The adoption of Law of Ukraine No. 3528-IX (2023) on the state regulation of the circulation of plants of the genus Cannabis liberalised the conditions for industrial hemp production, setting the permissible level of tetrahydrocannabinol at 0.3% and permitting the use of all parts of the plant in economic activities. Deregulation has contributed to a reduction in administrative costs, an increase in the economic efficiency of cultivation, and the creation of conditions for the restoration of processing infrastructure. In this context, the resumption of industrial hemp cultivation has taken on additional significance as a factor in strengthening the agricultural sector's potential for CO_2 sequestration by crops.

As noted by S. Amaducci *et al.* (2015), the key objective of hemp cultivation is to achieve high biomass accumulation rates, and the crop itself is characterised by relatively simple and low-cost cultivation technologies. Given that the volume of CO_2 absorption is directly dependent on the accumulated plant biomass, these characteristics of the crop indicate its significant potential as a tool for carbon sequestration in agricultural systems. Furthermore, a study by E. Campiglia *et al*. (2020) notes that the cultivation of industrial hemp is characterised by a relatively low need for capital investment and can be carried out using simplified technologies. Based on data on sown areas (Fig. 1), the potential carbon sequestration volumes of industrial hemp in Ukraine for the period 2020-2025 were calculated under three scenarios (Table 3).

***Table 3**. Potential carbon sequestration volumes by industrial hemp in Ukraine for the period 2020-2025 under three scenarios*

	Biomass accumulation rate	**Annual sequestration volume per 1 ha**	**Sequestration volume for the period 2020-2025**
Low scenario	8.55-9.81 tonnes/ha	15.5 tonnes of CO_2 per hectare per year	1.05 million tonnes CO_2
Medium scenario	8-12 tonnes/ha	16.5 tonnes of CO_2 per hectare per year	1.12 million tonnes CO_2
High scenario	15 tonnes/ha	24.75 tonnes of CO_2 per hectare per year	1.68 million tonnes CO_2

***Source:** compiled by the author*

For a total cultivated area of 11.3 thousand hectares, it was determined that under the low scenario for the period from 2020 to 2025, industrial hemp, under conditions of minimal biomass accumulation, absorbed approximately 15.5 tonnes of CO_2 per hectare per year. This corresponds to a cumulative sequestration volume of about 1.05 million tonnes of CO_2 over six years. The medium scenario indicates that under average agro-climatic conditions and typical yield levels, the average absorption amounts to 16.5 tonnes of CO_2 per hectare per year. Over the period 2020-2025 and with an area of 11.3 thousand hectares, the total sequestration is estimated at approximately 1.12 million tonnes of CO_2, which significantly exceeds direct emissions associated with diesel fuel use in the baseline cultivation model. The high scenario assumes that, taking into account optimal biomass growth, an extended growing season, and intensive agricultural technologies, the sequestration level may reach 24.75 tonnes of CO_2 per hectare per year. Under these conditions, the total CO_2 absorption by industrial hemp across 11.3 thousand hectares amounts to approximately 1.68 million tonnes of CO_2.

It should be noted separately that the obtained volumes of CO_2 absorption by industrial hemp did not initially account for greenhouse gas emissions associated with cultivation operations. Thus, for an accurate assessment of the net carbon balance of the agroecosystem, it is appropriate to compare the CO_2 absorption potential of plant biomass with emissions arising from, in particular, the use of fuel and lubricants for field operations, application of plant protection products, harvesting, and related activities. The assessment of energy inputs in the baseline cultivation model indicates that approximately 159.9 litres of diesel fuel are required per hectare of industrial hemp crops. Using the emission factor of 2.63 kg CO_2 per litre, confirmed by combustion stoichiometry, the emissions amount to:

$$159.9\ \text{L} \times 2.63\ \text{kg}\ CO_2/\text{L} = 420.54\ \text{kg}\ CO_2. \tag{3}$$

Following the calculation of potential carbon sequestration volumes by industrial hemp in Ukraine for the period 2020-2025 under three scenarios (Table 3), it was established that under the low scenario the estimated absorption amounts to 15.5 tonnes of CO_2 per hectare per year. Considering that the baseline cultivation model for 1 hectare requires 159.9 litres of diesel fuel, direct emissions from complete combustion, using the adopted factor of 2.63 kg CO_2 per litre, are equal to 0.421 tonnes of CO_2 per hectare (3). The comparison shows that absorption under the low scenario exceeds direct CO_2 emissions from diesel use by approximately 36.8 times, with a difference of about 15.1 tonnes of CO_2 per hectare. Under the calculated medium scenario, the estimated absorption for industrial hemp is 16.5 tonnes of CO_2 per hectare per year, exceeding direct CO_2 emissions from diesel by approximately 38 times, with a difference of about 16.1 tonnes of CO_2 per hectare. Under the high scenario, absorption exceeds direct CO_2 emissions from diesel use by approximately 58.8 times, with a difference of about 24.3 tonnes of CO_2 per hectare. Taking the above into account, it can be concluded that direct CO_2 emissions from diesel use per hectare are relatively small compared to the magnitude of the potential carbon sequestration by industrial hemp biomass.

The findings of S.M. Madden *et al*. (2022) have demonstrated the potential environmental benefits of growing industrial hemp. This is also evident in the present study, as a synthesis of the findings suggests that industrial hemp possesses high climate potential as a crop with intensive biomass accumulation and significant CO_2 sequestration capacity. Even under a low-carbon absorption scenario, the carbon absorbed by industrial hemp significantly exceeds the direct emissions associated with the use of diesel fuel during cultivation, indicating a positive net carbon balance at the agroecosystem level. At the same time, the estimates obtained reflect only the initial stage of the climate effect and do not take into account the impact of the use of plant protection products, nor the subsequent accumulation or release of CO_2 during the processing, use and disposal of hemp products. This is confirmed by the study by A. Pawar *et al*. (2026), particularly regarding the need to account for the carbon content accumulated in above-ground and below-ground biomass.

As noted in the study by C. Schluttenhofer & L. Yuan (2017), the cultivation of industrial hemp requires further research, as the global production market has growth potential. This statement is consistent with the authors' research; to assess the effectiveness of industrial hemp's actual contribution to achieving carbon neutrality in the agricultural sector, an in-depth analysis of the product's full life cycle is advisable – from cultivation and primary processing of biomass to its end uses. A similar view regarding the need to investigate all aspects related to factors that potentially influence carbon sequestration by industrial hemp, such as soil type, climate and agricultural practices, in order to define industrial hemp as an environmentally friendly crop, is shared by the authors A. Suardi *et al*. (2024).

In contrast to the authors' study, there is debate in the scientific literature regarding the environmental viability of growing even organic hemp, as its impact on the environment is not unequivocally positive and depends on production technology and the subsequent use of biomass. As demonstrated by Z. Shen *et al*. (2022), the climate impact of hemp cultivation involves trade-offs: leaving plant residues in the soil contributes to an increase in organic carbon stocks, but does not provide effective climate change mitigation, whereas the use of biomass for the production of durable biomaterials yields a more pronounced long-term climate effect.

In particular, a study by M. Meffo Kemda *et al*. (2024) showed that, alongside the positive effects (the ability to absorb and store carbon), it is necessary to take into account the emissions arising at various stages of production, as some hemp processing products are climate-neutral: for example, the production of oil and flour is accompanied by significant emissions that are not fully offset by carbon sequestration; furthermore, the environmental impacts of processing and packaging play an important role, as they also contribute to the overall carbon footprint of production. This is also confirmed by a study by I. Bošković & A. Radivojević (2023), which demonstrates a pessimistic scenario regarding the impact of industrial hemp on the carbon balance throughout its life cycle, due to the possibility that greenhouse gas emissions may exceed absorption over the product's full life cycle.

Summarising the results obtained in the context of existing scientific research, it can be stated that industrial hemp demonstrates high climate potential as a crop with intensive biomass accumulation and significant CO_2 sequestration capacity. At the same time, as the literature review indicates, the assessment of the actual climate effect is ambiguous and depends significantly on cultivation technology, the uses of biomass, and the accounting of emissions at all stages of the production chain. Thus, the results of this study are consistent with the broader scientific debate regarding the potential of industrial hemp as a tool for decarbonisation, whilst emphasising the need for a comprehensive approach to assessing its carbon balance.

CONCLUSIONS

The study confirmed the high climatic potential of industrial hemp (*Cannabis sativa* L.) as a tool for atmospheric carbon sequestration in Ukraine's agricultural sector. During its short growing season, the crop is capable of accumulating significant amounts of carbon, making it a promising tool for carbon farming and climate-oriented agricultural practices. A "digital twin" model of a 1-hectare hemp field, developed for the typical soil and climatic conditions of the Ukrainian Forest-Steppe, enabled a quantitative assessment of the ratio between biological CO_2 absorption during biomass formation and direct emissions associated with the use of diesel fuel in agricultural operations. It was found that the potential CO_2 absorption from 1 ha over a single growing season ranges from 15.5 tonnes under a low dry biomass yield scenario to 24.75 tonnes under a high scenario. At the same time, direct CO_2 emissions associated with the combustion of diesel fuel in the baseline cultivation model are estimated at around 0.421 tonnes CO_2/ha, demonstrating the significant dominance of sequestration processes over agricultural emissions. Under the medium scenario, absorption exceeds direct emissions by approximately 38 times, confirming the formation of a positive net carbon balance within the agroecosystem.

Scenario modelling, based on official statistics regarding the areas under industrial hemp cultivation in Ukraine in 2020-2025, showed that under the medium scenario, the total sequestration potential could exceed 1.1 million tonnes of CO_2 over the specified period. Even with relatively small cultivation areas, this highlights the crop's significant contribution to achieving decarbonisation goals and strengthening the role of agriculture as a compensatory sector in the national carbon balance. The results obtained confirmed the feasibility of integrating industrial hemp into carbon farming programmes, climate policies and sustainable land use strategies. The high rate of biomass accumulation over a short growing season allows industrial hemp to be considered an effective tool for rapidly offsetting a portion of anthropogenic CO_2 emissions. However, the assessment conducted covered mainly the cultivation and harvesting stages and did not account for the likely use of fertilisers, post-harvest processing, biomass processing, long-term storage, or the re-release of carbon in end products. Thus, industrial hemp should be viewed not merely as an agricultural crop, but as an element of an integrated climate strategy, the effectiveness of which is determined by a combination of agricultural technologies, the spatial distribution of crops and the development of processing infrastructure, as well as its potential to contribute to sustainable agricultural development in Ukraine.

Prospects for further research involve extending the "digital twin" model to cover the full product life cycle, accounting for changes in soil organic carbon stocks, regional variations in growing conditions, and scenarios for the use of hemp biomass with varying durations of biogenic carbon sequestration. The further development of such models may provide a foundation for establishing a system of quantitative accounting of the climatic effects of industrial hemp within national decarbonisation policy and carbon farming frameworks.

ACKNOWLEDGEMENTS

None.

FUNDING

The study was conducted without financial support.

CONFLICT OF INTEREST

No conflict of interest exists in relation to this study, including financial, personal, authorship or any other conflict that could influence the conduct of the study and the results presented in this article.

REFERENCES

[1] Ahmed, A.T.M.F., Islam, Z., Mahmud, S., Sarker, E., & Islam, R. (2022). Hemp as a potential raw material toward a sustainable world: A review. *Heliyon*, 8(1), article number e08753. doi: 10.1016/j.heliyon.2022.e08753.

[2] Akbarian-Saravi, N., Sowlati, T., & Milani, A.S. (2025). Cradle-to-gate life cycle assessment of hemp utilization for biocomposite pellet production: A case study with data quality assurance process. *Cleaner Engineering and Technology*, 27, article number 101027. doi: 10.1016/j.clet.2025.101027.

[3] Amaducci, S., Scordia, D., Liu, F.H., Zhang, Q., Guo, H., Testa, G., & Cosentino, S.L. (2015). Key cultivation techniques for hemp in Europe and China. *Industrial Crops and Products*, 68, 2-16. doi: 10.1016/j.indcrop.2014.06.041.

[4] Arehart, J.H., Nelson, W.S., & Srubar, W.V. (2020). On the theoretical carbon storage and carbon sequestration potential of hempcrete. *Journal of Cleaner Production*, 266, article number 121846. doi: 10.1016/j.jclepro.2020.121846.

[5] Bošković, I., & Radivojević, A. (2023). Life cycle greenhouse gas emissions of hemp-lime concrete wall constructions in Serbia: The impact of carbon sequestration, transport, waste production and end of life biogenic carbon emission. *Journal of Building Engineering*, 66, article number 105908. doi: 10.1016/j.jobe.2023.105908.

[6] Campiglia, E., Gobbi, L., Marucci, A., Rapa, M., Ruggieri, R., & Vinci, G. (2020). Hemp seed production: Environmental impacts of *Cannabis sativa* L. agronomic practices by life cycle assessment (LCA) and carbon footprint methodologies. *Sustainability*, 12(16), article number 6570. doi: 10.3390/su12166570.

[7] Cortés, J.G., Ryu, B.R., Pauli, C., Barroso, L.R., & Park, S.-H. (2024). Industrial applications of hemp fiber in Europe and evolving regulatory landscape. *Journal of Natural Fibers*, 21(1), article number 2435047. doi: 10.1080/15440478.2024.2435047.

[8] Drozd, O.M., Shuvar, A.M., & Shuvar, N.B. (2025). Scientific substantiation of the realization of the potential of industrial crops in agrotechnologies of the Forest-Steppe of Ukraine (review). *Agrarian Innovations*, 30, 69-77. doi: 10.32848/agrar.innov.2025.30.10.

[9] European Commission. (n.d.a). *Hemp*. Retrieved from https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en?utm.

[10] European Commission. (n.d.b). *The European Green Deal*. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[11] Regulation (EU) 2021/1119 of the European Parliament and of the Council "Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')". (2021, June). Retrieved from https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng.

[12] Food and Agriculture Organization of the United Nations. (2021). *The state of the world's land and water resources for food and agriculture: Systems at breaking point*. Retrieved from https://openknowledge.fao.org/server/api/core/bitstreams/ecb51a59-ac4d-407a-80de-c7d6c3e15fcc/content.

[13] Hemp CBD Business Plans. (2026). *Hemp CBD legalization world map: January 2026 Updated*. Retrieved from https://hempcbdbusinessplans.com/hemp-legalization-world-map/.

[14] Intergovernmental Panel on Climate Change. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Retrieved from https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf.

[15] Laiko, H. (2023). Record yield of stalks and fiber of Glukhivski 51 or Industrial hemp for the bioeconomy. *Institute of Bast Crops, National Academy of Agrarian Sciences of Ukraine*. Retrieved from https://surl.li/dvhflg.

[16] Law of Ukraine No. 3528-IX "On Amendments to Certain Laws of Ukraine on the State Regulation of the Circulation of Cannabis Plants (Cannabis)". (2023, December). Retrieved from https://zakon.rada.gov.ua/laws/show/en/3528-20#Text.

[17] Madden, S.M., Ryan, A., & Walsh, P. (2022). A systems thinking approach investigating the estimated environmental and economic benefits and limitations of industrial hemp cultivation in Ireland from 2017-2021. *Sustainability*, 14(7), article number 4159. doi: 10.3390/su14074159.

[18] Meffo Kemda, M., Marchi, M., Neri, E., Marchettini, N., & Niccolucci, V. (2024). Environmental impact assessment of hemp cultivation and its seed-based food products. *Frontiers in Environmental Science*, 12, article number 1342330. doi: 10.3389/fenvs.2024.1342330.

[19] Michels, M., Brinkmann, A., & Mußhoff, O. (2025). Economic, ecological and social perspectives of industrial hemp cultivation in Germany: A qualitative analysis. *Journal of Environmental Management*, 389, article number 126117. doi: 10.1016/j.jenvman.2025.126117.

[20] Mishchenko, S., & Laiko, I. (2024). Breeding and genetic innovations in hemp cultivation and their methodological support: Directions, achievements, and prospects. In *Scientific support for the development of hemp cultivation in the 21st century* (pp. 34-63). Sumy: Tsoma S.P. doi: 10.48096/monograph.2024.34-63.

[21] Nazari, F., & Woods, D. (2025). Environmental life cycle assessment of hemp-based thermal insulation: From agricultural growth to manufacturing in the United States. *Journal of Cleaner Production*, 506, article number 145509. doi: 10.1016/j.jclepro.2025.145509.

[22] Nykoliuk, O., & Sych, K. (2025). Industrial hemp production and processing: Current state, trends, and challenges. *Kyiv School of Economics*. Retrieved from https://kse.ua/wp-content/uploads/2025/04/Hemp-EU-1.0-Eng.pdf.

[23] Pawar, A., Sagan, V., Alifu, H., Tamang, K.R., Bagnall, G.C., Gul, C., Shrestha, N., Lopes, F.A., Topp, C.N., & Valliyodan, B. (2026). A novel approach to estimate total carbon accounting for below and above-ground carbon content of industrial hemp with UAV LiDAR and hyperspectral data fusion. *Smart Agricultural Technology*, 13, article number 101897. doi: 10.1016/j.atech.2026.101897.

[24] Roik, M.V., Kravchuk, V.I., Kvak, V.M., & Borivskyi, A.F. (2024). Study of the principles and strategic directions of cultivation and use of industrial hemp in Ukraine. *Bioenergy*, 1, 4-7. doi: 10.47414/be.2024.no1.pp4-7.

[25] Schluttenhofer, C., & Yuan, L. (2017). Challenges towards revitalizing hemp: A multifaceted crop. *Trends in Plant Science*, 22(11), 917-929. doi: 10.1016/j.tplants.2017.08.004.

[26] Shen, Z., Tiruta-Barna, L., & Hamelin, L. (2022). From hemp grown on carbon-vulnerable lands to long-lasting bio-based products: Uncovering trade-offs between overall environmental impacts, sequestration in soil, and dynamic influences on global temperature. *Science of The Total Environment*, 846, article number 157331. doi: 10.1016/j.scitotenv.2022.157331.

[27] State Statistics Service of Ukraine. (n.d.). *Dataset explorer*. Retrieved from https://stat.gov.ua/uk/explorer?md5=4d81b063981cf07b29c77e0c2a15426c.

[28] Suardi, A., Bravo, I., Beni, C., Papetti, P., & Rana, R.L. (2024). Carbon footprint of hemp and sunflower oil in southern Italy: A case study. *Ecological Indicators*, 160, article number 111786. doi: 10.1016/j.ecolind.2024.111786.

Оцінка вуглецевого балансу вирощування промислових конопель в Україні та їх вплив на досягнення вуглецевої нейтральності

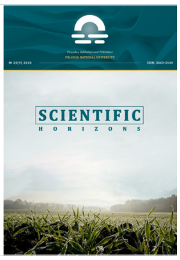
Ірина Грузінська
Аспірант
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0009-0007-6579-316X

Анотація. Метою дослідження було визначення кліматичного потенціалу промислових конопель як інструменту секвестрації вуглецю та оцінка їх внеску у досягнення вуглецевої нейтральності аграрного сектору України. У роботі застосовано системний аналіз сучасних наукових досліджень, аналіз офіційних статистичних даних щодо площ вирощування промислових конопель, а також елементи підходу оцінювання повного життєвого циклу для ідентифікації джерел викидів у технологічному ланцюгу вирощування. Для кількісної оцінки кліматичного ефекту розроблено розрахункову модель «цифрового двійника» конопляного поля площею один гектар для типових ґрунтово-кліматичних умов Лісостепу України. На основі моделювання «цифрового двійника» конопляного поля та розрахункових параметрів сформовано три сценарії секвестрації вуглецю: низький, середній та високий, що відображають мінімальні, середні та максимальні показники урожайності біомаси. Встановлено, що за низького, середнього та високого сценаріїв потенційні обсяги поглинання становлять відповідно близько 15,5, 16,5 та 24,75 тонн CO_2 з 1 га за один вегетаційний період. Водночас прямі викиди CO_2 від спалювання дизельного пального для обробітку поля у базовій моделі вирощування оцінено на рівні близько 0,421 тонн CO_2/га, що свідчить про суттєве переважання процесів секвестрації над агротехнологічними викидами. За низького сценарію обсяг поглинання перевищує прямі викиди приблизно у 36,8 рази, за середнього – приблизно у 38 разів, а за високим – у 58,8 раз. Сценарне моделювання, яке розроблено на основі офіційних статистичних даних щодо площ вирощування промислових конопель, засвідчило, що навіть за невеликих посівних площ вирощування промислових конопель показало позитивну динаміку у досягненні цілі декарбонізації та підвищення ролі сільського господарства у національному вуглецевому балансі. Практична цінність дослідження полягає у можливості використання отриманих результатів для обґрунтування програм вуглецевого фермерства, інтеграції промислових конопель у кліматичну політику та планування розвитку переробної інфраструктури

Ключові слова: декарбонізація сільського господарства; секвестрація; зміна клімату; біомаса; сценарне моделювання

ISSN 2663-2144
e-ISSN 2709-8877

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 29(1), 89-101
UDC 636.2+631.4+574+637.5+504.5
DOI: 10.48077/scihor1.2026.89



Sustainable and regenerative cattle production systems: Literature review

Fernando Mata[*]
PhD, Senior Researcher
National Zootechnical Station, National Institute of Agricultural and Veterinary Research
2005-424, Prof. Dr. Vaz Portugal Str., Vale de Santarém, Portugal
https://orcid.org/0000-0002-5687-7114

Article's History:
Received: 14.10.2025
Revised: 06.03.2026
Accepted: 25.03.2026
Published: 06.04.2026

Abstract. Cattle production remains relevant to global food systems due to its links with food security, environmental impacts, animal welfare, and societal expectations. The purpose of this review was to examine the role of beef and dairy cattle within sustainable and regenerative agricultural systems using an integrated, systems-based perspective. The review was based on a critical synthesis of peer-reviewed literature addressing environmental performance, methane emissions, animal welfare, regenerative management practices, and socio-economic dimensions of cattle production. Sustainability frameworks used in cattle systems were analysed, with particular attention to the limitations of single-metric assessments such as greenhouse gas emissions. The biological basis of methane production and its relationship with feed efficiency, animal health, and management was described. Evidence on regenerative beef and dairy practices, including grazing management, soil carbon dynamics, biodiversity outcomes, and nutrient cycling, was examined. The role of animal welfare was analysed through One Health, One Welfare, and One Biology frameworks, highlighting its integration with productivity, emissions intensity, and system resilience. Gaps in current sustainability assessments and research methodologies were identified, particularly regarding long-term system performance, welfare indicators, and policy coherence. The findings of this review can be used by researchers, policymakers, advisors, and farmers to support the design, assessment, and implementation of cattle systems that align productivity with environmental stewardship and animal welfare

Keywords: agroecosystems; animal welfare; greenhouse gas emissions; methane mitigation; one health; one welfare; regenerative agriculture

INTRODUCTION

Cattle production (beef and dairy) remains a cornerstone of global agricultural systems, providing milk, meat, and ecosystem services while supporting the livelihoods of hundreds of millions of people worldwide. S.E. Place (2024) emphasised that ruminant livestock, including cattle, possess a digestive physiology that enables them to convert fibrous and otherwise non-human-edible forage into nutrient-dense meat and milk, and concluded that this capacity allows cattle to contribute uniquely to sustainable food systems by

Suggested Citation:
Mata, F. (2026). Sustainable and regenerative cattle production systems: Literature review. *Scientific Horizons*, 29(1), 89-101 doi: 10.48077/scihor1.2026.89.

[*] *Corresponding author*

producing high-quality human nutrition from marginal resources. A. Domínguez-Hernández *et al.* (2025) further showed that cattle have historically stimulated mixed crop-livestock systems by recycling nutrients through manure and converting forages and crop residues into food, forming the agronomic basis of both traditional systems such as the Norfolk rotation and modern integrated and regenerative farming approaches.

Sustainability in cattle systems is inherently multidimensional, encompassing environmental integrity, animal welfare, economic viability, and social acceptability. N. Britten & S. Mahendran (2025) emphasised that sustainability assessments have historically prioritised environmental indicators such as land use, water consumption, and greenhouse gas (GHG) emissions, often neglecting animal welfare and biological functioning. S.J. Hendriks *et al.* (2025) argued that welfare should be integrated as a core sustainability component rather than treated as an ethical add-on. Among environmental concerns, GHG emissions from cattle have received particular attention. S. Malyugina *et al.* (2025) quantified enteric methane emissions as a significant component of global agricultural methane output and identified enteric fermentation as the dominant source. J.V.A. Muller (2025) noted that this has driven climate policy and research to focus strongly on methane mitigation strategies.

Cattle systems vary widely in structure and impact, ranging from intensive feed-based systems to extensive grazing systems embedded within complex landscapes. R. Teague & U. Kreuter (2020) demonstrated that well-managed grazing systems can enhance soil carbon storage, nutrient cycling, and habitat provision, particularly when aligned with regenerative or agroecological principles. In contrast, X. Niu *et al.* (2025) showed that poorly managed systems, regardless of intensity, can contribute to land degradation, biodiversity loss, and compromised animal welfare. These findings highlighted the need for sustainability assessments that evaluate management quality and context rather than generic comparisons of cattle versus alternative food systems. Animal welfare represents a critical but often underrepresented pillar of sustainable cattle production. L. Boyle & P. Stevenson (2025) reported that poor health, chronic stress, and suboptimal living conditions reduce productivity and increase resource use per unit of output. Methane emissions must therefore be interpreted within a broader biological and management context. B.-R. Min *et al.* (2022) showed that enteric methane represents an energetic loss of 2-12% of gross energy intake and concluded that strategies improving feed efficiency and rumen function can reduce emissions per unit of product. H.R. Albarki *et al.* (2025) provided evidence that nutritional interventions, genetic selection for feed efficiency, and improved pasture quality can simultaneously enhance productivity, welfare, and emissions performance. These authors highlighted that such approaches align with regenerative principles by optimising biological function rather than targeting methane reduction in isolation. Regenerative cattle farming has emerged as a proposed pathway to reconcile production with ecological restoration.

N. Adams *et al.* (2025) highlighted policy pressures to reduce agricultural emissions alongside rural development goals. Sustainability strategies must balance environmental performance, ethical considerations, and farmer livelihoods to maintain social legitimacy. These findings reinforced the need for integrative frameworks that recognise cattle as biological agents within complex agroecosystems rather than solely as sources of environmental burden. This review aimed to clarify how cattle production systems can contribute to sustainability and regeneration when evaluated through integrated environmental, animal welfare, and socio-economic perspectives. Specifically, the objectives were to: (i) examine how management-driven improvements in biological efficiency and animal welfare influence environmental performance, including emissions intensity; (ii) assess the potential and limitations of regenerative beef and dairy systems across different production contexts; and (iii) identify key gaps in current sustainability frameworks that arise from reliance on single metrics, particularly methane emissions.

A narrative review approach was employed to synthesise current knowledge on sustainable and regenerative cattle systems. Peer-reviewed literature published primarily between 2019 and 2025 was identified using targeted searches in the major scientific databases (Web of Science, and Scopus) with keywords related to cattle production, sustainability, methane mitigation, animal welfare, and regenerative agriculture. Sources were selected based on relevance, methodological robustness, and applicability to beef and dairy systems, and were analysed thematically to integrate findings across environmental, biological, and socio-economic dimensions.

ANIMAL WELFARE AND ONE HEALTH

Animal welfare has emerged as a critical component of sustainability assessments in livestock production, particularly for cattle, as societal expectations increasingly demand that welfare outcomes be considered alongside environmental and economic performance L. Boyle & P. Stevenson (2025) emphasised that societal pressure is driving the integration of welfare considerations into sustainability frameworks, while Q. Zhang *et al.* (2023) highlighted that ignoring welfare may undermine the perceived legitimacy of livestock systems.. Traditional sustainability frameworks often focus on measurable metrics such as GHG emissions or land use, but this narrow focus can overlook welfare dimensions that are inherently biological, behavioural and affective in nature. Contemporary animal welfare science emphasised that welfare is not simply the absence of disease or stress but also includes the animal's ability to express natural behaviours, maintain good health, and achieve a positive mental state, elements captured in established conceptual models such as the Five Domains framework. The One Health paradigm, endorsed by global health authorities, recognises the interdependence of human, animal and ecosystem health, and it has become foundational in understanding complex agro-ecosystem challenges. S.J. Pitt & A. Gunn (2024) argued that One Health promotes interdisciplinary collaboration to address shared threats such as zoonoses, antimicrobial resistance, and food safety, yet they note that broader welfare outcomes are often underemphasised.

However, One Health traditionally emphasises disease and health outcomes more than broader welfare concerns. This has led to the development of One Welfare, an extension of One Health that explicitly integrates animal welfare with human well-being and environmental sustainability within a single comprehensive framework. S. Platto *et al.* (2025) argued that One Welfare recognises the bidirectional relationship between animal and human welfare and their joint dependency on environmental integrity. The relevance of One Welfare to livestock systems is notable: production animals such as cattle not only influence but are influenced by the health and well-being of their caretakers, consumers and the ecosystems they live in. C. Spigarelli *et al.* (2021) demonstrated that improvements in animal welfare can enhance farmer satisfaction and ecosystem services, suggesting practical benefits beyond ethical considerations. In the context of regenerative agriculture, systematic analysis illustrated that current research often links animal welfare outcomes to animal health and human financial or psychological well-being, and environmental conservation. M.J. Hargreaves-Méndez & M.J. Hötzel (2023) concluded that welfare actions are integral to broader sustainability goals, reinforcing the need to move beyond narrow environmental or economic metrics. Despite the conceptual advances, operationalising One Welfare within cattle production systems remains challenging, as welfare assessments are variably integrated into sustainability models. A. van der Linden *et al.* (2020) observed that many decision-support tools still inadequately capture welfare alongside environmental and socio-economic indicators, limiting their utility for holistic system management.

The literature argued that embedding welfare into sustainability requires systems-level thinking and interdisciplinary collaboration across veterinary science, animal behaviour, ecology, public health and policy domains. C. Ducrot *et al.* (2024) emphasised that integrating welfare indicators with societal outcomes, such as public trust, is essential for resilient and socially acceptable livestock systems. In practical terms, welfare improvements can enhance production efficiency and reduce disease burdens. J.K. Lane *et al.* (2025) found that interventions such as improved housing and nutrition reduced infectious disease incidence, thereby decreasing antimicrobial use and associated costs, aligning with One Health goals. Although much of the One Welfare literature remained emergent S. Platto *et al.* (2025) pointed out that welfare must be central to sustainability evaluations, not merely an ethical add-on.

A One Biology perspective emphasises that biological processes across levels, from microbial communities to whole animals and ecosystems, are interconnected and collectively shape sustainability outcomes. Y. Xie *et al.* (2022) highlighted that the rumen microbiome drives nutrient metabolism, feed efficiency, and methane emissions while influencing host physiology, illustrating how microbe-host dynamics underpin sustainable cattle performance. X. Liu *et al.* (2023) extended this view to soil-plant-animal microbiomes, demonstrating that microbial diversity supports ecosystem function, nutrient cycling, and resilience, providing a biological foundation for One Health and holistic sustainability. As shown in Figure 1, the making of a regenerative cattle production system is conceptualised through the integration of societal expectations into the complementary frameworks of One Health, One Welfare, and One Biology, emphasising the interdependence of animal, human, and ecosystem processes.

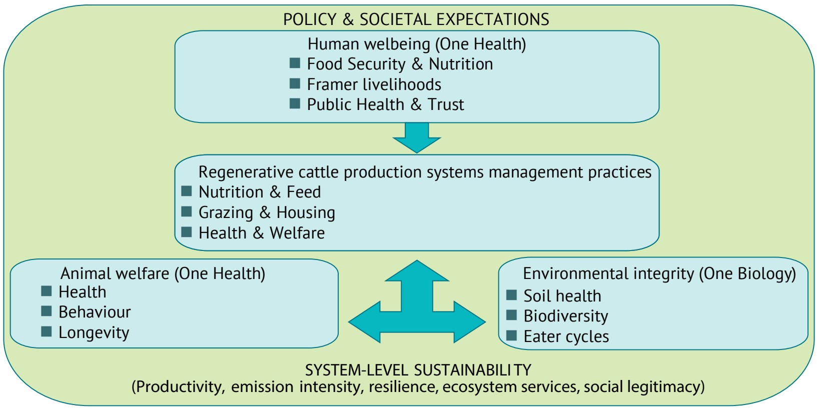


***Figure 1**. The making of a regeneratiuve cattle production system*

***Source:** created by the author*

Overall, the convergence of the concepts of "One Health," "One Welfare," and "One Biology" demonstrated that animal welfare cannot be considered a peripheral component of sustainable livestock development, but must be integrated into the design and evaluation of the system. Welfare outcomes have a biological basis, are mediated by social factors, and are conditioned by environmental conditions, linking productivity, emission intensity, public trust, and ecosystem resilience within a single integrated system. Therefore, the regenerative cattle production model requires coordinated assessment tools that simultaneously consider health, behavior, microbiology, and socio-economic aspects. The inclusion of welfare in interdisciplinary, systemic management is a prerequisite for creating livestock systems that are scientifically sound, ethically justified, and environmentally sustainable in the long term.

SUSTAINABILITY AND REGENERATION PRACTICES IN CATTLE PRODUCTION SYSTEMS: BEEF CATTLE

Beef cattle production occupies a central yet contested role in global food systems. The environmental footprint of beef cattle is characterised by multiple interacting pressures. C. Evangelista *et al*. (2024) quantified enteric methane as a dominant contributor to agricultural GHG emissions, while H. Guo *et al*. (2022) demonstrated that beef has one of the highest emissions intensities per unit of protein among livestock products. However, these emissions are part of a larger suite of environmental impacts that include land conversion, nutrient runoff, soil degradation and biodiversity loss. D.J. Eldridge *et al*. (2022) argued that focusing solely on carbon obscures these co-occurring pressures. Well-managed grazing systems can influence some of these outcomes positively. Strategic grazing, where cattle are moved across paddocks or pasture cells in ways that allow vegetation recovery and minimise bare ground, has been shown to improve or maintain soil health and reduce nitrate runoff compared with continuous grazing.

In beef systems, regenerative approaches typically involve rotational or adaptive grazing, integration with crop systems or silvopastoral designs, and management practices that encourage ecological flows. P.L. Peri *et al*. (2024) described regenerative grazing as a systems-based approach that reconnects livestock management with ecological processes. U. Khatri-Chhetri *et al*. (2022) found that rotational grazing reduced overgrazing and improved root development, while C.D. Morris (2021) highlighted its role in stimulating soil biological activity and manure distribution. While the precise outcomes depend on context, grazing that prevents vegetation from being consumed below critical thresholds can promote plant recovery and resilience. Systems thinking research further shows that improved grazing and manure management can create feedback loops. K.M. Brewer *et al*. (2023) demonstrated that better soil structure enhances forage quality, which improves cattle nutrition and productivity, while L.O. Tedeschi *et al*. (2024) linked these gains to improved economic performance and stewardship outcomes. Together, these positive loops showed how ecological and production goals can be aligned when cattle are managed as part of an integrated system rather than isolated production units.

One of the core regenerative claims is that cattle managed on permanent pastures can increase soil organic carbon and support broader ecosystem functions . Q. Zhang *et al*. (2023) reported that well-managed grazing improves soil structure, increases below-ground carbon storage and stimulates microbial activity essential for soil fertility. However, the magnitude and longevity of carbon sequestration from regenerative grazing remains debated. S. Ren *et al*. (2024) synthesised evidence showing that while soil carbon gains are possible, sequestration rates vary widely and are temporally limited. A.T. Simmons *et al*. (2026) documented measurable soil carbon increases under managed grazing, whereas K. Georgiou *et al*. (2022) cautioned that soils can reach saturation points, constraining long-term sequestration. Y. Wang *et al*. (2023), alongside S. Ren *et al*. (2024), argued that pasture-based sequestration alone cannot offset methane emissions but may contribute as part of a broader mitigation portfolio that also targets methane and nitrous oxide. Regenerative beef systems can also impact biodiversity and hydrological functions. Y. Wang *et al*. (2026) showed that managed grazing regimes that limit compaction and maintain permanent, diverse plant cover enhance habitat heterogeneity and ecosystem resilience. Regenerative practices can also improve hydrological performance. T.F. Döbert *et al*. (2021) demonstrated that restored soil structure increases infiltration capacity, while G. Agunbiade *et al*. (2025) found that improved plant cover reduced runoff and erosion, contributing to drought resilience and reduced reliance on irrigation.

Adoption of regenerative practices in beef systems is influenced by socio-economic drivers and policy contexts. C. Moisés *et al*. (2025) showed that incentives such as carbon markets, certification schemes and emissions reporting frameworks can motivate farmers to document and adopt soil- and ecosystem-enhancing practices. C. Early (2025) highlighted Brazil as a case where pasture improvement, agroforestry integration and methane-reducing feeds are being trialled to reduce deforestation while enhancing productivity. However, C. Moisés *et al*. identified gaps in technical knowledge, high initial costs, and limited access to finance as major barriers, especially for smallholder farmers.

Sustainable development and restoration of beef cattle farming systems depend on moving beyond the assessment of individual issues and recognizing cattle as an active component of agroecosystems. Evidence showed that adaptive grazing, nutrient cycling, biodiversity enhancement, and soil management can deliver additional environmental and production benefits, but results remain dependent on specific conditions and cannot be considered universal. Soil carbon sequestration and improved ecosystem services can make a significant contribution to mitigation and resilience, but they do not eliminate the need to directly address methane and other greenhouse gas emissions. Therefore, the long-term sustainability of beef cattle systems requires integrated environmental management combined with a supportive policy framework, economic incentives, and robust monitoring that aligns environmental management with viable farm livelihoods.

SUSTAINABILITY AND REGENERATION PRACTICES IN CATTLE PRODUCTION SYSTEMS: DAIRY CATTLE

Regenerative dairy farming shares similarities with regenerative beef farming but also exhibits distinct characteristics, as summarised in Table 1. The dairy cattle sector faces substantial sustainability challenges. R.W. McDowell *et al.* (2022) identified dairy systems as among the leading contributors to agricultural GHG emissions. A comprehensive understanding of dairy sustainability, therefore, must extend beyond simple productivity metrics. M. Bojovic & A. McGregor (2023), who emphasised regenerative capacity and social equity as essential components of long-term dairy system viability.

***Table 1**. Comparative table of regenerative beef and dairy cattle production systems*

Aspect	Regenerative beef systems	Regenerative dairy systems
Production focus	Typically, on extensive or semi-intensive pastures.	Usually pasture-based or mixed crop-livestock systems.
Grazing management	Rotational/adaptive grazing, silvopastoral integration, strategic forage recovery.	Rotational grazing, forage diversification, integration with cover crops or forage crop rotation.
Animal welfare	Emphasis on natural behaviours, reduced stocking stress, improved longevity and health.	Pasture access, improved housing, lameness prevention, metabolic and reproductive health management.
Feed efficiency	Optimised through forage quality, supplementation, and adaptive grazing.	Balanced diets, pasture quality, supplementation, feed monitoring, and reduced metabolic stress.
Environmental outcomes	Soil carbon accumulation, improved soil structure, nutrient cycling, biodiversity enhancement, water infiltration.	Soil carbon retention, nutrient recycling through manure, reduced synthetic fertiliser use, enhanced biodiversity in pastures.
Green house gas mitigation	Partial offset via soil carbon; methane reduction achieved via improved forage quality, animal health, and genetics.	Partial offset via soil carbon; reduced emissions intensity per litre of milk through improved feed efficiency and animal welfare.
Biodiversity impacts	Increased habitat heterogeneity, pollinator support, microbial diversity.	Enhanced pasture flora diversity, improved soil microbiome, support for beneficial insects.
Socio-economic aspects	Often more suitable for smallholders or marginal lands; requires knowledge-intensive management; influenced by carbon markets and regenerative certification.	Requires infrastructure for milk collection/processing; knowledge-intensive; economic viability supported by productivity and ecosystem service incentives.
Resilience & sustainability	High resilience to drought and marginal lands if properly managed; multifunctional landscapes.	Resilient systems, diversified forage, integrated crop-livestock rotations; reduces reliance on external inputs.

***Source:** compiled by the author*

One of the perennial sustainability concerns in dairy production is its environmental footprint. J. Herron *et al.* (2022) demonstrated through life cycle assessment that enteric methane from ruminal fermentation constitutes a major share of dairy GHG emissions, while C. Galloway *et al.* (2024) showed that the magnitude of these emissions varies widely across regions and management systems. Pasture-based systems generally produce GHG emissions in the range of ~0.8 to 1.7 kg CO_2-eq/kg of fat- and protein-corrected milk. These studies consistently identified enteric methane and manure management as dominant emission sources, while also showing that herd productivity, feed quality and analytical boundaries strongly influence reported outcomes. Environmental impacts extend beyond climate change. R. Hu *et al.* (2024) demonstrated that dairy manure and fertiliser application are major sources of nitrogen and phosphorus losses to water bodies, while A.B. Leytem *et al.* (2021) linked pasture and feed-crop mismanagement to soil degradation. Together these impacts revealed the tightly coupled nature of dairy production and ecosystem processes, supporting the conclusion that sustainability assessments must address multiple impact categories rather than rely on single indicators.

Animal welfare is a key sustainability dimension in dairy systems, and welfare outcomes are increasingly integrated into dairy research and practice. A.B. Petrean *et al.* (2024) found that pasture access and well-designed housing systems reduce lameness and improve cow comfort. Systematic reviews by M. Verdon *et al.* (2025) showed a substantial increase in pastoral dairy welfare research, particularly in nutrition, behavioural expression and environmental conditions. These authors converged on the conclusion that healthy cows with good welfare status exhibit higher lifetime productivity and longevity, reduce resource use per unit of output, and experience lower disease burdens, aligning welfare improvements with One Health objectives. Regenerative agriculture seeks not just to sustain current conditions but to restore and strengthen ecological function. L.M. Alderkamp *et al*. (2025) documented a growing application of regenerative principles in pasture-based and mixed crop-livestock dairy systems. Although the academic literature on dairy-specific regenerative agriculture remained emergent, these authors emphasised that ecological benefits depend strongly on local adaptation and management context.

Regenerative dairy practices include rotational grazing, cover cropping, crop rotations, integration of livestock with arable production, and reduced external inputs. B. Emmett *et al*. (2025) described these practices as mechanisms for enhancing soil organic matter and system resilience. Empirical studies by S. Zhu *et al*. (2024) showed that such practices increase microbial diversity, improve water infiltration, reduce erosion and support habitat provision. D. Finlay (2024) argued that these outcomes represent a shift from extractive dairy production toward landscape-level regeneration. For example, O. Obasoro *et al*. (2025) demonstrated that mixed-species pastures increase biological nitrogen fixation via legumes, reduce dependence on synthetic fertilisers, and enhance soil structure and carbon stocks. X. Niu *et al*. (2025) further showed that improved soil biodiversity, including beneficial microbes and earthworms, enhances nutrient cycling and reduces nutrient runoff risks. Together, these studies illustrated that dairy cattle integrated into diversified landscapes can contribute positively to ecosystem services rather than degrade them.

Dairy farms that prioritise regenerative practices can also support biodiversity outcomes. A. Sher *et al*. (2024) found that managed grazing supports mosaics of plant communities that benefit invertebrates, pollinators and soil organisms. S. Lv *et al*. (2024) showed that increasing grassland diversity through rotational grazing and forage diversification maintains habitat complexity and strengthens ecological networks. These outcomes are consistently more favourable in grass-based systems than in confined systems, particularly where permanent pastures are maintained. Linking livestock to landscape function also entails improved nutrient flow management. Z.K. Al-Musawi *et al*. (2025) demonstrated that recycling dairy manure within crop rotations improves soil fertility and reduces reliance on synthetic fertilisers, thereby lowering eutrophication risks in adjacent water bodies.

Adopting regenerative and sustainable dairy practices is influenced by economic and policy frameworks. E. Bull *et al*. (n.d.), through the Regen Dairy project, illustrated how collaboration between farmers and global food companies can co-develop farmer-centric regenerative models that enhance biodiversity while maintaining productivity and profitability. These authors emphasised that regenerative dairy must be locally adapted and embedded within. whole-system response to climate, biodiversity and food security challenges. However, E. Bull *et al*. identified upfront transition costs, infrastructure requirements and knowledge gaps as major constraints, particularly in the absence of strong market incentives. They argued that policy instruments such as payments for ecosystem services, certification schemes, carbon markets and targeted research support are critical for scaling regenerative dairy practices. While regenerative approaches offer pathways to enhance ecological integrity, Y. Wang *et al*. (2023) cautioned against overstating their climate mitigation potential. Authors showed that soil carbon sequestration is context-dependent and subject to saturation, and that gains from regeneratively managed pastures do not fully offset enteric methane emissions. Consequently, these authors concluded that regenerative practices must be integrated with methane mitigation strategies, improved genetics, manure management and enhanced feed efficiency to achieve meaningful sustainability outcomes.

Taken together, the evidence suggests that the future sustainability of dairy systems hinges on improving biological efficiency rather than simply reducing scale or intensifying inputs. Dairy cattle convert human-inedible biomass into high-value nutrients, and when embedded within diversified crop–livestock systems, they can close nutrient loops and stabilise agroecosystem functioning. At the same time, unresolved trade-offs between productivity, methane emissions, nutrient leakage and welfare performance highlight the need for transparent, multi-criteria evaluation frameworks. The transition toward regenerative dairy therefore represents not a single practice shift, but a systemic redesign that aligns metabolic efficiency, ecological restoration and socio-economic viability within regionally adapted production models.

REFRAMING SUSTAINABILITY IN CATTLE PRODUCTION SYSTEMS: BEYOND SINGLE METRICS. METHANE EMISSIONS

This review revealed that sustainability in cattle production cannot be adequately assessed through isolated indicators such as GHG emissions or land-use efficiency alone. While methane emissions from enteric fermentation remain a legitimate concern, an exclusive focus on methane, risks overshadowing the broader biological, ecological, and socioeconomic roles of cattle within agroecosystems. The evidence reviewed supports a reframing of sustainability as a multidimensional framework containing aspects of environmental integrity, animal welfare, system productivity, economic viability, and social legitimacy. Cattle, as ruminants, occupy a distinct niche in food systems by converting fibrous biomass into high-quality human nutrition while interacting dynamically with soils, plants, and microbial communities. Sustainability outcomes, therefore, depend less on the mere presence of cattle and more on how, where, and within which management frameworks they are integrated. This systems perspective is increasingly aligned with regenerative and agroecological paradigms, which emphasise functional outcomes, such as soil health, biodiversity, and resilience, rather than narrow efficiency metrics.

Methane mitigation remains a critical component of climate strategies for cattle systems, but its interpretation requires nuance. Enteric methane represents an energetic loss to the animal and is influenced by diet composition, rumen function, health status, and overall management. I. Kyriazakis *et al.* (2024) demonstrated that improvements in feed efficiency and forage quality reduce methane emissions per unit of output, while S. Malyugina *et al.* (2025) showed that animal health and longevity further lower emissions intensity by spreading production over a longer productive lifespan. These studies consistently indicated that methane reductions often emerge as co-benefits of welfare-oriented and regenerative management, rather than as outcomes of emission-targeted interventions alone. Short-lived climate pollutants such as methane also differ fundamentally from carbon dioxide in atmospheric behaviour, revealing the importance of temporal and systems-level perspectives when evaluating climate impacts. The reviewed evidence supported the position that methane mitigation should be embedded within integrated strategies that enhance biological efficiency and ecosystem function rather than pursued as a stand-alone objective.

A central finding of this review was that animal welfare functions not merely as an ethical consideration but as a critical driver of sustainability outcomes. J.L. Capper & P. Williams (2023) showed that poor welfare, manifested through chronic stress, disease, or lameness, reduces productivity and increases resource use per unit of output, while T.S. Winton *et al.* (2024) linked welfare deficits to reduced system resilience. Conversely, systems that prioritise cattle welfare consistently demonstrate improvements in longevity, reproductive performance, feed efficiency, and emissions intensity. The integration of welfare within sustainability frameworks is strengthened by the One Welfare concept, which explicitly links animal welfare, human well-being, and environmental integrity. A. Diana *et al.* (2020) provided early empirical evidence that welfare-positive systems reduce disease prevalence and antimicrobial use, while L. Boyle & P. Stevenson (2025) demonstrated links between improved animal welfare, farmer satisfaction and mental health. S. Platto *et al.* (2025) synthesised this evidence to argue that welfare improvements often generate simultaneous benefits across animal, human and environmental domains. Despite these links, the authors collectively noted that welfare remains inconsistently incorporated into sustainability assessment tools, suggesting a need for more comprehensive indicators that capture animal-based measures alongside environmental and economic metrics.

In regenerative contexts, welfare gains often emerge indirectly through management practices such as pasture access, adaptive grazing and reduced stocking stress. These approaches enable cattle to express natural behaviours, including grazing, social interaction and movement, while reducing the chronic pressures associated with confinement or overstocking. Improved comfort and behavioural freedom are commonly linked with better hoof condition, lower stress levels and improved overall health status. At the same time, these management strategies support vegetation recovery and soil function, illustrating that animal well-being and environmental performance can develop in parallel.

REGENERATIVE CATTLE PRODUCTION SYSTEMS: POTENTIAL AND CONSTRAINTS

Regenerative beef production systems demonstrate clear potential to improve soil health, biodiversity, and nutrient cycling when grazing is well managed. J. Mehre *et al.* (2024) reported that rotational and adaptive grazing enhance soil structure, promote perennial root systems and stimulate microbial activity, while A.T. Simmons *et al.* (2026) linked these changes to improved long-term productivity. These outcomes are particularly relevant in regions where beef cattle utilise marginal lands unsuitable for cropping, reinforcing their role in multifunctional landscapes rather than purely extractive production systems. However, the climate mitigation potential of regenerative beef systems remains contested. C. Rousset *et al.* (2024) cautioned that soil carbon sequestration rates are highly context-dependent and may plateau over time, limiting long-term mitigation potential. While soil carbon gains can partially offset emissions, the evidence consistently suggests that regenerative grazing alone is unlikely to render beef production climate-neutral. This reveals the importance of avoiding overgeneralised claims and instead adopting transparent, site-specific assessments.

Beyond carbon, regenerative beef systems contribute meaningfully to biodiversity conservation, hydrological regulation, and landscape heterogeneity. These benefits are often absent from conventional life cycle assessments, yet are central to ecosystem sustainability. Socio-economic factors, including access to knowledge, finance, and supportive policy instruments, remain decisive in determining adoption rates, particularly among smallholders. Scaling regenerative beef production, therefore, requires institutional support alongside scientific validation. Dairy production presents distinct sustainability challenges due to its intensity, nutrient flows, and reliance on high productivity per animal. Nevertheless, R. Teague & U. Kreuter (2020) showed that regenerative principles can be successfully applied to dairy systems, particularly in pasture-based and mixed crop-livestock contexts. Practices such as rotational grazing, forage diversification, cover cropping, and integrated manure management can enhance soil health, reduce nutrient losses, and improve biodiversity outcomes. Animal welfare plays a particularly salient role in dairy sustainability. As with beef systems, regenerative dairy practices should not be viewed as a singular climate solution. Y. Wang *et al*. (2023) showed that soil carbon sequestration contributes to mitigation but does not negate the need for methane-reducing feed additives, genetic selection for efficiency and precision nutrient management. The emerging consensus is that regenerative dairy systems are most effective when embedded within holistic sustainability strategies rather than promoted through simplified climate narratives.

Overall, regenerative cattle production systems offer a credible pathway to enhance ecological function, animal welfare and system resilience, but their benefits are conditional rather than automatic. Outcomes depend on context-specific management, realistic expectations regarding carbon sequestration, and integration with complementary mitigation strategies targeting methane and nutrient losses. Both beef and dairy sectors demonstrate that regeneration is most effective when embedded within multifunctional landscape management and supported by coherent policy and economic frameworks. Long-term credibility therefore requires transparent measurement, interdisciplinary governance and alignment between environmental goals, productivity and farmer livelihoods.

SOCIETAL EXPECTATIONS, POLICY, AND SYSTEM LEGITIMACY: FUTURE RESEACH DIRECTIONS

The long-term viability of cattle production systems is increasingly shaped by societal expectations regarding environmental responsibility, animal welfare, and transparency. F. Mata & I. Domingues (2025) argued that public trust depends not only on emissions reductions but also on visible commitments to ethical animal treatment and land stewardship. Regenerative and welfare-oriented systems may therefore enhance social licence by aligning production practices with consumer and policy priorities. Policy frameworks that reward ecosystem services, welfare outcomes, and verified sustainability performance are likely to be pivotal in supporting transition pathways. Carbon markets, regenerative certification schemes, and payments for biodiversity or water regulation services offer potential mechanisms but require robust, standardised metrics to avoid greenwashing and ensure credibility. Importantly, farmer livelihoods must remain central to these frameworks; sustainability transitions that undermine economic viability risk low adoption and social resistance.

Despite the rapid growth of literature on sustainable and regenerative cattle production, important knowledge gaps persist that limit robust system-level evaluation and effective policy alignment. Addressing these gaps is essential for positioning cattle systems within global sustainability agendas, including the United Nations Sustainable Development Goals (SDGs) (United Nations, 2026). The research community should aim for long-term, integrated experimental research that simultaneously evaluates productivity, GHG emissions, soil carbon dynamics, biodiversity, nutrient cycling, and animal welfare. Most current studies focused on isolated indicators or short time frames, which constrains their relevance to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Long-term trials are particularly important for assessing the durability of soil carbon sequestration and ecosystem service gains, given growing evidence of saturation limits and vulnerability to climate variability. Coordinated research networks across agro-ecological zones would improve the robustness and comparability of sustainability claims. Future research must also explicitly integrate animal welfare into sustainability assessment frameworks, aligning livestock research with SDG 3 (Good Health and Well-Being) and SDG 12. While substantial evidence links improved welfare to enhanced productivity, longevity, and reduced emissions intensity, welfare indicators are rarely embedded within life cycle assessments or whole-farm sustainability models. Developing standardised, animal-based welfare metrics that can be incorporated alongside environmental and economic indicators would strengthen One Welfare approaches and improve the ethical credibility and societal relevance of sustainability evaluations.

Context-specific methane mitigation research remains a critical priority for SDG 13. Many mitigation strategies have been developed under confined or high-input systems, with limited validation in pasture-based, mixed, or regenerative cattle systems. Future research should assess how dietary strategies, grazing management, rumen microbiome function, and genetic selection interact under diverse production contexts, while also considering impacts on animal health and welfare. Emphasis should be placed on mitigation approaches that deliver co-benefits for productivity and resilience, rather than narrowly targeting methane reduction alone. Soil carbon and ecosystem service research must move beyond offset-centric narratives to support SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation). While regenerative grazing and integrated crop-livestock systems can enhance soil organic carbon, water infiltration, nutrient retention, and biodiversity, reliance on soil carbon sequestration as a long-term offset for ruminant emissions carries substantial risk. Future studies should therefore prioritise realistic assessments of sequestration potential, permanence, and trade-offs, while placing greater emphasis on multifunctional ecosystem outcomes rather than single carbon metrics.

Social and economic dimensions of system adoption require far greater research attention to support SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). Farmer decision-making is influenced by labour requirements, financial risk, knowledge access, market structures, and policy incentives, yet these factors remain underrepresented in biophysical studies. Comparative and participatory research approaches are needed to identify region-specific barriers and enablers of adoption, particularly for small- and medium-scale producers whose livelihoods are closely tied to cattle production. Future research should also address policy coherence, governance, and sustainability assessment methodologies, directly contributing to SDG 17 (Partnerships for the Goals). Aligning climate mitigation targets, agri-environmental schemes, animal welfare regulations, and market-based instruments is essential to avoid incentivising narrow techno-fixes or unintended environmental and social trade-offs. Advances in systems modelling, interdisciplinary assessment frameworks, and stakeholder-engaged research will be critical for evaluating cattle production as a dynamic component of agro-ecosystems rather than solely as a source of emissions.

Cattle production systems interact directly with multiple dimensions of the SDGs, including food security, climate action, ecosystem integrity, human well-being, and rural livelihoods. Because cattle systems simultaneously influence nutrition provision (SDG 2), greenhouse gas emissions (SDG 13), land and water resources (SDGs 6 and 15), animal and human health (SDG 3), and socio-economic resilience in rural communities (SDGs 8 and 10), they represent a critical leverage point for achieving integrated sustainability outcomes. Explicitly linking future cattle research to the SDGs is therefore essential for ensuring that scientific advances inform policy, guide investment priorities, and support coherent, systems-based transitions rather than fragmented or single-issue interventions. Embedding SDG alignment within research agendas also strengthens the societal relevance, legitimacy, and global comparability of sustainability assessments in cattle production.

CONCLUSIONS

Beef cattle sustainability and regeneration interact actively. Regenerative beef systems offer pathways to integrate ecological restoration with productive agriculture, enhancing soil health, promoting biodiversity, supporting water function, and increasing resilience, but they are not a universal solution. Outcomes depend on how cattle are managed, where they are kept, and how human and ecological needs are balanced. Achieving meaningful sustainability in beef production thus demands system-level, evidence-based assessments that embrace both environmental and regenerative principles, recognising cattle as part of dynamic agroecosystems rather than discrete production machines. Sustainability and regeneration in dairy cattle systems require holistic, systems-level approaches that integrate environmental, animal welfare, social and regenerative principles. Dairy systems must be evaluated not only for their productivity but for their ecological contributions, such as soil carbon, biodiversity, water quality, nutrient cycling, and for their socio-economic resilience. Appropriately managed, regenerative dairy cattle systems can transition from being a source of environmental pressure to co-designers of healthier agroecosystems, though this depends on context, management quality and supportive policy frameworks.

This review supported the conclusion that cattle can contribute to sustainable and regenerative agricultural systems when managed within integrative frameworks that prioritise biological function, animal welfare, and ecosystem health. Methane mitigation remains necessary but insufficient as a singular goal. Instead, sustainability gains emerge most consistently where welfare-positive management, regenerative practices, and system optimisation converge. Advancing such systems will require robust science, transparent metrics, supportive policy, and recognition of cattle as active participants in complex agro-ecosystems rather than solely as sources of environmental burden. Continued rigorous research and transparent assessment frameworks are essential to understand the regenerative potential of both beef and dairy systems and to guide science-based decision-making. Future research priorities should address the need for integrative, long-term, and context-specific evidence to support cattle production systems that contribute meaningfully to multiple SDGs, balancing food provision, environmental stewardship, animal welfare, and socio-economic resilience.

ACKNOWLEDGEMENTS

None.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The author declares no conflicts of interest.

REFERENCES

[1] Adams, N., Sans, A., Trier Kreutzfeldt, K.-E., Arias Escobar, M.A., Oudshoorn, F.W., Bolduc, N., Aubert, P.-M., & Smith, L.G. (2025). Assessing the impacts of EU agricultural policies on the sustainability of the livestock sector: A review of the recent literature. *Agriculture and Human Values*, 42, 193-212. doi: 10.1007/s10460-024-10595-y.

[2] Agunbiade, G., Sahoo, D., O'Halloran, L., Silva, L., & Malcomson, H. (2025). Impact of silvopasture on soil health and water quality in the Southeast USA: A review. *Journal of Hydrology: Regional Studies*, 59, article number 102448. doi: 10.1016/j.ejrh.2025.102448.

[3] Albarki, H.R., Suntara, C., Wongtangtintharn, S., Iwai, C.B., Jayanegara, A., & Cherdthong, A. (2025). Sustainable animal nutrition and feeding strategies for reducing methane emissions and enhancing feed digestibility with encapsulated black soldier fly larvae oil. *Sustainability*, 17(7), article number 3155. doi: 10.3390/su17073155.

[4] Alderkamp, L.M., Klootwijk, C.W., Schut, A.G.T., van der Linden, A., van Middelaar, C.E., & Taube, F. (2025). Integrating crop and dairy production systems: Exploring different strategies to achieve environmental targets. *Science of The Total Environment*, 958, article number 177990. doi: 10.1016/j.scitotenv.2024.177990.

[5] Al-Musawi, Z.K., Vona, V., & Kulmány, I.M. (2025). Utilizing different crop rotation systems for agricultural and environmental sustainability: A review. *Agronomy*, 15(8), article number 1966. doi: 10.3390/agronomy15081966.

[6] Bojovic, M., & McGregor, A. (2023). A review of megatrends in the global dairy sector: What are the socioecological implications? *Agriculture and Human Values*, 40(1), 373-394. doi: 10.1007/s10460-022-10338-x.

[7] Boyle, L., & Stevenson, P. (2025). Sustainability of livestock production: Raising the profile of animal welfare and the risks with "techno-fixes". *Animal Frontiers*, 15(5), 47-57. doi: 10.1093/af/vfaf034.

[8] Brewer, K.M., Muñoz-Araya, M., Martinez, I., Marshall, K.N., & Gaudin, A.C.M. (2023). Long-term integrated crop-livestock grazing stimulates soil ecosystem carbon flux, increasing subsoil carbon storage in California perennial agroecosystems. *Geoderma*, 438, article number 116598. doi: 10.1016/j.geoderma.2023.116598.

[9] Britten, N., & Mahendran, S. (2025). Environmental sustainability and ruminant production: A UK veterinary perspective. *Veterinary Record*, 196(1), article number e4703. doi: 10.1002/vetr.4703.

[10] Bull, E., Costain, F., Thorsen, Ø., & Bright, A. (n.d.). *Let's get serious about making dairy regenerative*. Retrieved from https://regendairy.org/wp-content/uploads/2024/09/Regen-Dairy-Report-FINAL-SEPT-24.pdf.

[11] Capper, J.L., & Williams, P. (2023). Investing in health to improve the sustainability of cattle production in the United Kingdom: A narrative review. *The Veterinary Journal*, 296-297, article number 105988. doi: 10.1016/j.tvjl.2023.105988.

[12] Diana, A., Lorenzi, V., Penasa, M., Magni, E., Alborali, G.L., Bertocchi, L., & De Marchi, M. (2020). Effect of welfare standards and biosecurity practices on antimicrobial use in beef cattle. *Scientific Reports*, 10(1), article number 20939. doi: 10.1038/s41598-020-77838-w.

[13] Döbert, T.F., Bork, E.W., Apfelbaum, S., Carlyle, C.N., Chang, S.X., Khatri-Chhetri, U., Silva Sobrinho, L., Thompson, R., & Boyce, M.S. (2021). Adaptive multi-paddock grazing improves water infiltration in Canadian grassland soils. *Geoderma*, 401, article number 115314. doi: 10.1016/j.geoderma.2021.115314.

[14] Domínguez-Hernández, A., Juárez-Velázquez, A., Domínguez-Hernández, E., Zepeda-Bautista, R., Hernández-Aguilar, C., & Domínguez-Hernández, M. (2025). Impact of the integration level in crop-livestock systems on biomass production, nutrient recycling, and energy efficiency. *Biomass*, 5(2), article number 19. doi: 10.3390/biomass5020019.

[15] Ducrot, C., *et al.* (2024). Animal board invited review: Improving animal health and welfare in the transition of livestock farming systems: Towards social acceptability and sustainability. *Animal*, 18(3), article number 101100. doi: 10.1016/j.animal.2024.101100.

[16] Early, C. (2025). The Brazil cattle farmers regenerating hope for the Amazon. *Thomson Reuters*. Retrieved from https://www.reuters.com/sustainability/land-use-biodiversity/brazil-cattle-farmers-regenerating-hope-amazon--ecmii-2025-10-28/.

[17] Eldridge, D.J., Ding, J., & Travers, S.K. (2022). A global synthesis of the effects of livestock activity on hydrological processes. *Ecosystems*, 25(8), 1780-1791. doi: 10.1007/s10021-022-00746-9.

[18] Emmett, B., *et al.* (2025). *Regenerative agriculture in the UK: An ecological perspective*. London: British Ecological Society.

[19] Evangelista, C., Milanesi, M., Pietrucci, D., Chillemi, G., & Bernabucci, U. (2024). Enteric methane emission in livestock sector: Bibliometric research from 1986 to 2024 with text mining and topic analysis approach by machine learning algorithms. *Animals*, 14(21), article number 3158. doi: 10.3390/ani14213158.

[20] Finlay, D. (2024). Can dairy farming be part of the solution? In J. D'Silva & C. McKenna (Eds.), *Regenerative farming and sustainable diets* (pp. 157-161). London: Routledge. doi: 10.4324/9781032684369.

[21] Galloway, C., Swanepoel, P.A., & Haarhoff, S.J. (2024). A carbon footprint assessment for pasture-based dairy farming systems in South Africa. *Frontiers in Sustainable Food Systems*, 8, article number 1333981. doi: 10.3389/fsufs.2024.1333981.

[22] Georgiou, K., *et al.* (2022). Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications*, 13(1), article number 3797. doi: 10.1038/s41467-022-31540-9.

[23] Guo, H., Su, Z., Yang, X., Xu, S., & Pan, H. (2022). Greenhouse gas emissions from beef cattle breeding based on the ecological cycle model. *International Journal of Environmental Research and Public Health*, 19(15), article number 9481. doi: 10.3390/ijerph19159481.

[24] Hargreaves-Mendez, M.J., & Hötzel, M.J. (2023). A systematic review on whether regenerative agriculture improves animal welfare: A qualitative analysis with a One Welfare perspective. *Animal Welfare*, 32, article number e36. doi: 10.1017/awf.2023.28.

[25] Hendriks, S.J., Schmitt, O., & Boyle, L. (2025). Rethinking sustainability: Recognizing animal welfare's critical role. *Animal Frontiers*, 15(2), 3-7. doi: 10.1093/af/vfaf005.

[26] Herron, J., O'Brien, D., & Shalloo, L. (2022). Life cycle assessment of pasture-based dairy production systems: Current and future performance. *Journal of Dairy Science*, 105(7), 5849-5869. doi: 10.3168/jds.2021-21499.

[27] Hu, R., Leytem, A.B., Moore, A.D., & Strawn, D.G. (2024). Long-term dairy manure amendment promotes legacy phosphorus build up and mobility in calcareous soils. *Journal of Environmental Quality*, 53(3), 365-377. doi: 10.1002/jeq2.20559.

[28] Khatri-Chhetri, U., Thompson, K.A., Quideau, S.A., Boyce, M.S., Chang, S.X., Kaliaskar, D., Bork, E.W., & Carlyle, C.N. (2022). Adaptive multi-paddock grazing increases soil nutrient availability and bacteria to fungi ratio in grassland soils. *Applied Soil Ecology*, 179, article number 104590. doi: 10.1016/j.apsoil.2022.104590.

[29] Kyriazakis, I., *et al.* (2024). Improve animal health to reduce livestock emissions: Quantifying an open goal. *Proceedings. Biological Sciences*, 291(2027), article number 20240675. doi: 10.1098/rspb.2024.0675.

[30] Lane, J.K., Kelly, T., Bird, B., Chenais, E., Roug, A., Vidal, G., Gallardo, R., Zhou, H., VanHoy, G., & Smith, W. (2025). A one health approach to reducing livestock disease prevalence in developing countries: Advances, challenges, and prospects. *Annual Review of Animal Biosciences*, 13, 277-302. doi: 10.1146/annurev-animal-111523-102133.

[31] Leytem, A.B., Williams, P., Zuidema, S., Martinez, A., Chong, Y.L., Vincent, A., Vincent, A., Cronan, D., Kliskey, A., & Wulfhorst, J.D. (2021). Cycling phosphorus and nitrogen through cropping systems in an intensive dairy production region. *Agronomy*, 11(5), article number 1005. doi: 10.3390/agronomy11051005.

[32] Liu, X., *et al.* (2023). Prairie agroecosystems: Interconnected microbiomes of livestock, soil and insects. *Agriculture*, 13(2), article number 326. doi: 10.3390/agriculture13020326.

[33] Lv, S., Huang, J., Liu, H., & Ma, S. (2024). Grazing effects on species diversity across different scales are related to grassland types. *BMC Plant Biology*, 24(1), article number 1103. doi: 10.1186/s12870-024-05812-z.

[34] Malyugina, S., Holik, S., & Horky, P. (2025). Mitigation strategies for methane emissions in ruminant livestock: A comprehensive review of current approaches and future perspectives. *Frontiers in Animal Science*, 6, article number 1610376. doi: 10.3389/fanim.2025.1610376.

[35] Mata, F., & Domingues, I. (2025). European union citizens' perception of the reasons for the cost of the common agricultural policy. *European Countryside*, 17(1), 137-152. doi: 10.2478/euco-2025-0007.

[36] McDowell, R.W., Rotz, C.A., Oenema, J., & Macintosh, K.A. (2022). Limiting grazing periods combined with proper housing can reduce nutrient losses from dairy systems. *Nature Food*, 3(12), 1065-1074. doi: 10.1038/s43016-022-00644-2.

[37] Mehre, J., Schneider, K., Jayasundara, S., Gillespie, A., & Wagner-Riddle, C. (2024). Adaptive multi-paddock grazing increases soil carbon stocks and decreases the carbon footprint of beef production in Ontario, Canada. *Journal of Environmental Management*, 371, article number 123255. doi: 10.1016/j.jenvman.2024.123255.

[38] Min, B.-R., Lee, S., Jung, H., Miller, D.N., & Chen, R. (2022). Enteric methane emissions and animal performance in dairy and beef cattle production: Strategies, opportunities, and impact of reducing emissions. *Animals*, 12(8), article number 948. doi: 10.3390/ani12080948.

[39] Moisés, C., Arrobas, M., Tsitos, D., Pinho, D., Rezende, R.F., & Rodrigues, M.Â. (2025). Regenerative agriculture: Insights and challenges in farmer adoption. *Sustainability*, 17(16), article number 7235. doi: 10.3390/su17167235.

[40] Morris, C.D. (2021). How biodiversity-friendly is regenerative grazing? *Frontiers in Ecology and Evolution*, 9, article number 816374. doi: 10.3389/fevo.2021.816374.

[41] Muller, J.V.A. (2025). Beef and dairy emissions: A diagnosis of the international legal order. *Journal of Environmental Law*, 37(3), 617-628. doi: 10.1093/jel/eqaf020.

[42] Niu, X., Hou, K., Zhang, X., Dong, M., Yang, Y., & Gu, Y. (2025). Earthworm abundances change the community structure and diversity of soil bacteria and fungi in a microcosm experiment. *Current Microbiology*, 83(1), article number 43. doi: 10.1007/s00284-025-04631-1.

[43] Obasoro, O., Shackleton, J., Grace, C., Kennedy, J., Oram, N.J., Sheridan, H., Schmidt, O., de Goede, R., & Hoffland, E. (2025). Multispecies swards improve nitrogen use efficiency and reduce nitrogen surplus in agricultural grasslands. *Plant and Soil*. doi: 10.1007/s11104-025-07568-3.

[44] Peri, P.L., Chará, J., Viñoles, C., Bussoni, A., & Cubbage, F. (2024). Current trends in silvopastoral systems. *Agroforestry Systems*, 98(7), 1945-1953. doi: 10.1007/s10457-024-01093-5.

[45] Petrean, A.B., Daina, S., Borzan, M., Macri, A.M., Bogdan, L., Lazar, E.A., & Popescu, S. (2024). Pasture access effects on the welfare of dairy cows housed in free-stall barns. *Agriculture*, 14(2), article number 179. doi: 10.3390/agriculture14020179.

[46] Pitt, S.J., & Gunn, A. (2024). The One Health concept. *British Journal of Biomedical Science*, 81, article number 12366. doi: 10.3389/bjbs.2024.12366.

[47] Place, S.E. (2024). Examining the role of ruminants in sustainable food systems. *Grass and Forage Science*, 79(2), 135-143. doi: 10.1111/gfs.12673.

[48] Platto, S., Normando, S., Serres, A., Manteca, X., & Temple, D. (2025). One welfare: Bibliometric review of world literature. *Frontiers in Veterinary Science*, 12, article number 1627981. doi: 10.3389/fvets.2025.1627981.

[49] Ren, S., Terrer, C., Li, J., Cao, Y., Yang, S., & Liu, D. (2024). Historical impacts of grazing on carbon stocks and climate mitigation opportunities. *Nature Climate Change*, 14(4), 380-386. doi: 10.1038/s41558-024-01957-9.

[50] Rousset, C., *et al.* (2024). What evidence exists relating the impact of different grassland management practices to soil carbon in livestock systems? A systematic map protocol. *Environmental Evidence*, 13(1), article number 22. doi: 10.1186/s13750-024-00345-2.

[51] Sher, A., Li, H., ullah, A., Hamid, Y., Nasir, B., & Zhang, J. (2024). Importance of regenerative agriculture: Climate, soil health, biodiversity and its socioecological impact. *Discover Sustainability*, 5, article number 462. doi: 10.1007/s43621-024-00662-z.

[52] Simmons, A.T., Ingram, L., McDonald, S., Kardailsky, I., & Badgery, W. (2026). Managed grazing incrementally increased soil organic carbon amid larger temporal trends in a temperate pasture system. *Agriculture, Ecosystems & Environment*, 396, article number 110010. doi: 10.1016/j.agee.2025.110010.

[53] Spigarelli, C., Berton, M., Corazzin, M., Gallo, L., Pinterits, S., Ramanzin, M., Ressi, W., Sturaro, E., Zuliani, A., & Bovolenta, S. (2021). Animal welfare and farmers' satisfaction in small-scale dairy farms in the Eastern Alps: A "One Welfare" approach. *Frontiers in Veterinary Science*, 8, article number 741497. doi: 10.3389/fvets.2021.741497.

[54] Teague, R., & Kreuter, U. (2020). Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Frontiers in Sustainable Food Systems*, 4, article number 534187. doi: 10.3389/fsufs.2020.534187.

[55] Tedeschi, L.O., Johnson, D.C., Atzori, A.S., Kaniyamattam, K., & Menendez III, H.M. (2024). Applying systems thinking to sustainable beef production management: Modeling-based evidence for enhancing ecosystem services. *Systems*, 12(11), article number 446. doi: 10.3390/systems12110446.

[56] United Nations (2026). *The 17 goals*. Retrieved from https://sdgs.un.org/goals.

[57] van der Linden, A., de Olde, E.M., Mostert, P.F., & de Boer, I.J.M. (2020). A review of European models to assess the sustainability performance of livestock production systems. *Agricultural Systems*, 182, article number 102842. doi: 10.1016/j.agsy.2020.102842.

[58] Verdon, M., Field, L., Schütz, K., & Bryant, R. (2025). Invited review: Animal welfare in pasture-based dairy systems – a systematic scoping review to identify progress, priorities, and future directions. *Journal of Dairy Science*, 108(12), 12924-12948. doi: 10.3168/jds.2025-26981.

[59] Wang, Y., de Boer, I.J.M., Persson, U.M., Ripoll-Bosch, R., Cederberg, C., Gerber, P.J., Smith, P., & van Middelaar, C.E. (2023). Risk to rely on soil carbon sequestration to offset global ruminant emissions. *Nature Communications*, 14(1), article number 7625. doi: 10.1038/s41467-023-43452-3.

[60] Wang, Y., *et al.* (2026). Rotational grazing enhances ecosystem multifunctionality in alpine pastoral grasslands. *Agriculture, Ecosystems & Environment*, 397, article number 110055. doi: 10.1016/j.agee.2025.110055

[61] Winton, T.S., Nicodemus, M.C., & Harvey, K.M. (2024). Stressors inherent to beef cattle management in the United States of America and the resulting impacts on production sustainability: A review. *Ruminants*, 4(2), 227-240. doi: 10.3390/ruminants4020016.

[62] Xie, Y., Sun, H., Xue, M., & Liu, J. (2022). Metagenomics reveals differences in microbial composition and metabolic functions in the rumen of dairy cows with different residual feed intake. *Animal Microbiome*, 4(1), article number 19. doi: 10.1186/s42523-022-00170-3.

[63] Zhang, Q., Lu, Y., Zhang, C., Yao, B., & Su, J. (2023). Effect of moderate livestock grazing on soil and vegetation characteristics in zokor mounds of different ages. *Scientific Reports*, 13(1), article number 12459. doi: 10.1038/s41598-023-39530-7.

[64] Zhu, S., Sainju, U.M., Zhang, S., Tan, G., Wen, M., Dou, Y., Yang, R., Chen, J., Zhao, F., & Wang, J. (2024). Cover cropping promotes soil carbon sequestration by enhancing microaggregate-protected and mineral-associated carbon. *Science of the Total Environment*, 908, article number 168330. doi: 10.1016/j.scitotenv.2023.168330.

Сталі та регенеративні системи виробництва великої рогатої худоби: огляд літератури

Фернандо Мата
Доктор філософії, старший науковий співробітник
Національна зоотехнічна станція Національного інституту аграрних і ветеринарних досліджень
2005-424, вул. професора доктора Ваша Португала, м. Валле-де-Сантарен, Португалія
https://orcid.org/0000-0002-5687-7114

Анотація. Виробництво великої рогатої худоби залишається важливим для глобальних продовольчих систем через його зв'язок із продовольчою безпекою, впливом на довкілля, добробутом тварин та очікуваннями суспільства. Метою цього огляду було дослідити роль м'ясної та молочної великої рогатої худоби в стійких та регенеративних сільськогосподарських системах з використанням інтегрованого, системного підходу. Огляд базувався на критичному узагальненні рецензованої літератури, що стосується екологічних показників, викидів метану, добробуту тварин, регенеративних методів управління та соціально-економічних аспектів виробництва великої рогатої худоби. Було проаналізовано рамки сталого розвитку, що використовуються в системах вирощування великої рогатої худоби, з особливою увагою до обмежень однопараметричних оцінок, таких як викиди парникових газів. Було описано біологічні основи виробництва метану та його взаємозв'язок з ефективністю годівлі, здоров'ям тварин та управлінням. Були розглянуті докази щодо регенеративних практик у виробництві яловичини та молочних продуктів, включаючи управління випасом, динаміку вуглецю в ґрунті, результати біорізноманіття та цикл поживних речовин. Роль добробуту тварин була проаналізована через рамки «Одне здоров'я», «Один добробут» та «Одна біологія», підкреслюючи її інтеграцію з продуктивністю, інтенсивністю викидів та стійкістю системи. Були виявлені прогалини в поточних оцінках стійкості та методологіях досліджень, зокрема щодо довгострокової ефективності системи, показників добробуту та узгодженості політики. Результати цього огляду можуть бути використані дослідниками, політиками, консультантами та фермерами для підтримки розробки, оцінки та впровадження систем вирощування великої рогатої худоби, які поєднують продуктивність з раціональним використанням природних ресурсів та добробутом тварин

Ключові слова: агроекосистеми; добробут тварин; викиди парникових газів; зменшення викидів метану; єдине здоров'я; єдиний добробут; регенеративне сільське господарство

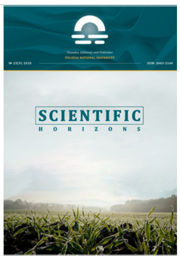
ISSN 2663-2144 e-ISSN 2709-8877

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 29(1), 102

DOI: 10.48077/scihor1.2026.102



Retraction:
“Use of contraceptives in cats with ovarian and uterine pathology”

The Editorial Board of Scientific Horizons hereby announces the retraction of the article “ Use of contraceptives in cats with ovarian and uterine pathology ” authored by O. Chekan, A. Rokochyi, O. Kysterna, Yu. Musiienko, and I. Levchenko published in Scientific Horizons, 2024, volume 27, No. 2, pages 9-18, DOI: https://doi.org/10.48077/scihor2.2024.09.

The decision to retract the article was made following an additional editorial review and independent external peer review initiated after substantiated concerns regarding the content of the publication were raised by a third party.

The repeated assessment identified substantial shortcomings, including discrepancies between certain citations and the content of the referenced sources, insufficient completeness of the description of materials and methods, limited statistical substantiation of the reported results, and inadequate evidential support for certain conclusions presented in the article. Taken together, these issues do not allow the published findings and conclusions to be considered sufficiently reliable for further scientific use.

In view of the above, the Editorial Board has decided to retract the article in accordance with the COPE principles of publication ethics and internationally recognised standards of academic integrity.

The authors were informed of the concerns and of the Editorial Board’s decision to retract the article.

The electronic version of the article will remain available in the journal archive as part of the scholarly record, clearly marked as Retracted.

The Editorial Board reaffirms its commitment to academic integrity, transparency of editorial procedures, and maintaining the quality of published research.

Відкликання статті
“Застосування протизаплідних засобів кішкам із патологією яєчників та матки”

Редакційна колегія журналу «Наукові горизонти» повідомляє про відкликання статті «Застосування протизаплідних засобів кішкам із патологією яєчників та матки» авторів О. Чекан, А. Рокочий, О. Кистерна, Ю. Мусієнко, І. Левченко, опублікованої у 2024 році, том 27, № 2, с. 9-18. DOI: https://doi.org/10.48077/scihor2.2024.09.

Рішення про відкликання статті було прийнято за результатами додаткової редакційної перевірки та незалежної зовнішньої рецензії, які були ініційовані після того, як третя сторона висловила обґрунтовані зауваження щодо змісту публікації.

Під час повторної експертизи було встановлено суттєві недоліки, зокрема невідповідність частини цитувань змісту наведених джерел, недостатню повноту опису матеріалів і методів дослідження, обмеженість статистичного обґрунтування результатів, а також недостатню доказовість окремих висновків статті. У сукупності зазначені обставини не дають можливості вважати представлені результати та висновки достатньо надійними для подальшого наукового використання.

З огляду на це редакційна колегія ухвалила рішення про відкликання статті відповідно до принципів публікаційної етики (COPE) та міжнародних стандартів академічної доброчесності.

Авторів було поінформовано про зауваження та рішення редакційної колегії щодо відкликання статті.

Електронна версія статті зберігатиметься в архіві журналу як частина наукового запису з чітким позначенням статусу Retracted.

Редакція журналу підтверджує відданість принципам наукової доброчесності, прозорості редакційних процедур і забезпеченню належної якості опублікованих матеріалів.

Corresponding author

Журнал
«НАУКОВІ ГОРИЗОНТИ»

Том 29, № 1
2026

Відповідальний редактор:
О. Кільніцька

Підписано до друку з оригінал-макета 25.03.2026
Ум. друк. арк. 12
Тираж 100 прим.

Видавництво: Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
Тел. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua

Journal
"SCIENTIFIC HORIZONS"

Volume 29, No. 1
2026

Managing Editor:
O. Kilnitska

Signed to the print with the original layout 25.03.2026
Conventional Printed Sheet 12
Circulation 100 copies

Publisher: Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
Tel. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/en