РОЗДІЛ 4

ЕКОЛОГІЗАЦІЯ СІЛЬСЬКОГО ГОСПОДАРСТВА

4.1. Ecologization of crop cultivation technologies in the Steppe zone of Ukraine under climate change conditions

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Agricultural production is a key sector of Ukraine's economy, especially in the Steppe zone, where vast areas of arable land are concentrated and a significant share of the gross harvest of grain, oilseed, and niche crops is formed. However, recent years have been marked by increasingly noticeable manifestations of climate change – rising air temperatures, more frequent droughts, moisture deficits during critical periods of vegetation, and reduced resilience of agroecosystems. These factors create new challenges for agricultural producers and require the rapid adoption of innovative technologies capable of ensuring stable yields and the rational use of natural resources.

Increasing the productivity of agricultural crops is possible through the combination of modern agronomic solutions, adaptive variety renewal, precision farming, the use of bioproducts, resource-saving and environmentally safe technologies, and other advanced practices.

Globally, particularly in the USA, Brazil, Argentina, Australia, Canada, and China, conservation agriculture is rapidly spreading. This approach is based on minimal soil tillage, permanent soil cover with plant residue mulch, and diversified crop rotation. Such technology improves soil structure, increases carbon content and microbial diversity, while also boosting yields and profitability. Since 2009, the global area under conservation agriculture has expanded by 10 million hectares annually, and by 2015–2016, 79 countries had adopted this practice. Reduced use of fossil fuels due to minimal soil disturbance can lower greenhouse gas emissions, making this technology climate-resilient [439].

Climate change is recognized as one of the most serious global threats to humanity, manifested through hazardous weather events such as extreme storms, abrupt weather shifts, floods, strong winds, heavy rainfall, hail, and prolonged droughts, all of which result in substantial ecological and economic losses worldwide. The growing unpredictability of climatic conditions poses a major risk to global food security. Scientific evidence indicates that without the implementation of adaptation measures in agriculture, its global output may

[439] Conservation agriculture impacts on productivity, resource-use efficiency and environmental sustainability: A holistic review / T. K. Das et al. *Indian Journal of Agronomy*. 2021. № 66 (5). P. 111–127.

decrease by up to 30 % by 2050 [440, 441]. Climatological studies have revealed that over the past two millennia, three warming phases and three cooling phases have occurred, the last of which ended in the first half of the 19th century. Since the mid-19th century, atmospheric temperatures initially stabilized, followed by a warming trend towards the end of the century, which reached 0.7–0.8 °C by the close of the 20th century. Projections suggest that near-surface air temperatures may rise by an additional 2–4.5 °C by the end of the 21st century [442]. The consequences of global climate change are increasingly evident in Ukraine as well. An analysis of the frequency of extreme weather events, particularly droughts, highlights a concerning upward trend. Over the past two decades, the mean annual temperature has risen by 0.8 °C, while average January and February temperatures have increased by 1–2 °C [443]. In the context of rapid global warming, it becomes essential to shift agricultural production towards more drought-resistant crops, such as durum wheat instead of soft wheat, chickpea instead of pea, and sorghum instead of maize [444].

In Ukraine, within the context of achieving the Sustainable Development Goals and adapting to climate change, an important focus is the decarbonization of agricultural production. Decarbonization is considered a key factor in enhancing the competitiveness of the agrarian sector under global climate challenges. At the same time, farmers require financial and organizational support in the process of transitioning to environmentally safe production [445].

Ukraine ranks among the top ten leaders in the global grain market. The natural conditions of the Steppe zone of Ukraine create favorable prerequisites for producing high-quality grain. Ensuring grain quality compliance with international standards is a priority area for the development of agricultural science. In this context, it is important to combine the productivity of cereal and leguminous crops with the economic efficiency and energy feasibility of their cultivation. A pressing task is the development of innovative grain cultivation technologies in the Steppe zone of Ukraine, with an emphasis on resource conservation, biologization, and the ecologization of production processes [446].

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443 Lindsey R., Dahlman L. Climate change: Global temperature. Understanding climate. 2025. URL: https://www.climate.gov/news-features/understanding-climate/ climate-change-global-temperature (дата звернення : 29.09.2025).

444 Korkhova M., Mykolaichuk V. Influence of weather conditions on the duration of interphysical periods and yield of durum winter wheat. *Scientific Horizons*. 2022. Vol. 25 (2). P. 36–46. doi: 10.48077/scihor.25(2).2022.36-46.

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[446] Sustainable agriculture in conditions of climate changes: Possible problems and ways of their solving in the South Steppe zone of Ukraine / R. A. Vozhehova et al. *Ukrainian Journal of Ecology*. 2018. Vol. 8 (3). P. 75–82.

Due to the intensive depletion of fossil fuels, renewable energy sources are becoming particularly relevant both globally and in Ukraine. The main forms of bioenergy include biofuels, biogas, and electricity produced from phytoenergetic crops [447, 448]. Such crops are characterized by high energy value and the ability to regenerate quickly. Modern technologies are aimed at making biofuel production more environmentally friendly, increasing its efficiency, and utilizing low-productive lands. The use of biomass from sorghum and asteraceae crops as fuel opens up prospects for strengthening energy independence, which is extremely important under current conditions. In addition, burning biomass or its deeper processing (production of bioethanol, biogas) is environmentally safe. Considering the consequences of military actions and the need for post-war recovery, the demand for biofuels and bioenergy equipment in Ukraine has significant prospects, creating favorable conditions for the active implementation of alternative energy sources [449, 450].

The cultivation of essential oil crops is relevant due to the growing demand for natural raw materials in the pharmaceutical, cosmetic, food, and perfume industries. These crops have high export potential and contribute to the diversification of agricultural production, while also improving soil ecological conditions and being suitable for cultivation on low-productive lands, which makes them important for sustainable agricultural development [451, 452].

In most farms of the Steppe zone of Ukraine, the yields of major crops and the profitability of crop production fluctuate significantly depending on meteorological and socio-economic conditions, indicating the instability of the agro-sphere in the southern region of the country. Under current economic conditions, a factor in enhancing competitiveness is not only high production efficiency but also the ability to promote oneself in agricultural markets, effectively represent one's enterprise, conduct tenders for resource procurement, and promptly obtain diverse information. Addressing these issues is possible only through the implementation of innovative agricultural technologies, the rational use of resources, and the ecologization of agricultural production.

Crop production in the Steppe zone of Ukraine, due to the specific climatic conditions of this region particularly the deficit of natural moisture alongside abundant solar energy and heat resources requires the application of a set of

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[447] Scientific and theoretical foundations and practical aspects of developing environmentally safe technologies for the cultivation and processing of sorghum in the steppe zone of Ukraine : monograph / M. I. Fedorchuk et al. Kherson, 2017. 208 p.

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scientifically and agrobiologically grounded technological measures aimed at achieving high, stable, and economically viable yields of agricultural crops.

When using irrigation in arid regions, it is essential to ensure the rational use of irrigation water, increase the efficiency of agroresources in terms of yield, and widely implement innovative artificial irrigation technologies (such as drip irrigation, computerized sprinkler systems, and evapotranspiration monitoring). Under non-irrigated conditions in the southern region, the urgent need is to introduce water- and resourcesaving technologies that can provide consistently high yields even under unfavorable weather conditions and limited rainfall.

Over the past decades, significant changes have occurred in crop cultivation technologies: new high-yielding varieties and hybrids have been developed, modern technological tools have appeared, and agro-economic relations at both micro- and macrolevels have evolved. In addition, new research results in crop production have been obtained and must be applied at the production level. However, issues of resource conservation, water-saving, biologization, as well as the economic and environmental justification of agricultural technologies, remain unresolved comprehensively, which highlights the need for relevant field research in this area.

Grain crops play a leading role in overall agricultural production. Crop farming in the Steppe zone specializes in the production of winter wheat, barley, corn, soybeans, sunflower and rapeseed seeds, as well as the cultivation of vegetable crops. In terms of production volume and profitability, the grain sector holds a leading position in the Steppe zone. Approximately 48 % of Ukraine's grain crop area is concentrated here, including 56 % of wheat, 48 % of barley, and 30 % of corn, with further expansion of its sown areas on irrigated lands [453].

In global crop production, grain crops occupy the largest sown areas, highlighting their extremely important role as food, feed, and raw material in the national economy. In Ukraine, the area under grain crops reaches 15.5–16.5 million hectares, or 45–50 % of the total sown area. The most widespread grain crop in Ukraine is winter wheat, with sown areas ranging from 6.4 to 7.3 million hectares depending on the year. Up to 90 % of its area is concentrated in the Steppe and Forest-Steppe zones, with only about 10 % in the Polissya region.

The two most common types of winter wheat are soft and hard wheat. Compared to soft wheat, hard wheat grain is richer in protein (16–18 %). Flour from hard wheat is an essential raw material for the pasta industry, as its gluten allows the production of pasta that retains its shape well during cooking. It is also used to produce a special type of flour semolinaand high-quality semolina grains.

Thanks to the widespread adoption of intensive winter wheat cultivation technologies in recent years, its average yield has significantly increased,

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reaching 4.02 t/ha. This demonstrates the high biological potential of winter wheat, the full realization of which is a primary goal for agronomists. However, in years with unfavorable weather conditions, the productivity of hard wheat significantly declines under production conditions, which is due to imperfect cultivation technologies and the uncertainty of the varietal composition suitable for irrigated conditions in the Southern Steppe of Ukraine [454].

Leguminous crops play a significant role in the development of the agricultural sector, as they contribute to strengthening food security, stimulate agricultural development, and support the sustainable development of rural areas. They are a valuable market component due to their diverse uses across various industries. The relevance of this issue is underscored by the fact that, despite growing demand, the level of legume cultivation and processing remains low, leading to product shortages and increased prices. Beyond their economic importance, research also focuses on the environmental aspect – preserving and enhancing soil fertility – since legumes perform a vital function in agroecosystems [455].

Leguminous crops have high nutritional value, as they contain a significant amount of protein – ranging from 20 to 30 % on a dry matter basis – making them important in the diet of both humans and animals. In addition, they are a source of energy used not only in the food industry but also in various production processes. Legumes positively impact the environment by improving soil structure, enhancing fertility and water permeability, which supports the cultivation of other crops. Their root systems help combat soil erosion by holding soil particles in place. Moreover, these crops contribute to increased biodiversity, serving as a food source for many insects, birds, and animals. Leguminous crops are also used to restore degraded soils, improve soil structure, and reduce depletion levels. Additionally, they can serve as a basis for producing organic fertilizers, providing an environmentally friendly alternative to chemical products [456].

The productivity of winter wheat and barley, as well as other cereal crops, largely depends on the varietal composition, with the influence of this factor reaching 50 % or more. Yield increases are accompanied by an enhanced response of varieties to high agronomic potential; however, as variety intensity increases, their adaptive potential gradually decreases. In recent years, the role of winter soft wheat as a primary food crop has grown due to two main factors: climate changes leading to higher overall temperatures, longer and more intense droughts, a more complex phytosanitary and entomological situation in

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cultivated and natural biocenoses, and the extended duration of autumn-winter vegetation of winter wheat. Currently, the nature of the wheat plant has been significantly altered: the genetic yield potential has increased 2.5–3.0 times (from 3.0–4.0 to 10.0–12.0 t/ha), and traits and properties related to resistance to frost, drought, diseases, and pests have been improved. However, in production, due to unfavorable weather conditions and violations of cultivation technologies, the genetic potential for yield and grain quality of winter soft wheat varieties is never fully realized. In recent years, the return from varietal potential has been particularly low for various reasons, with actual yields reaching only 28–32 % of the genetic potential of modern varieties. Several studies have been dedicated to the ecological plasticity and stability of winter wheat varieties, as well as the relationship between yield and parameters of ecological plasticity. Utilizing the existing ecological resilience of winter wheat varieties should be considered one of the main conditions for achieving their potential productivity under adverse environmental conditions.

The influence of agrotechnological factors on the productivity, quality, and adaptability of winter wheat varieties. Wheat grain is used worldwide as a staple food. The three most widely cultivated types of wheat are common (*Triticum aestivum*), durum (*T. durum*), and club, or compact (*T. compactum*) wheat. Wheat is grown as a commercial crop due to its relatively high yield, good performance in temperate climates with a short growing season, and its ability to produce high-quality flour. Most wheat flour is used to produce bread, pasta, cereals, pastries, cookies, and similar products. Additionally, wheat is utilized for the production of starch, malt, dextrose, gluten, alcohol, and other products. Wheat contains approximately 13% protein and serves as a primary source of plant-based protein in the human diet. It is also an important source of carbohydrates, and when consumed as whole-grain products, wheat provides dietary fiber.

In 2025, China, India, and Russia remain the leading wheat producers, followed by the United States, France, and Canada. Ukraine is a major global producer and exporter of wheat. In 2025, the country ranks 9th among the largest wheat exporters (~20.7–26.8 million tons). Ukraine plays a significant role in global grain exports, including wheat, making the improvement of crop productivity, enhancement of grain quality, and production of environmentally safe products particularly relevant today [457].

Field experiments in the arid zone of the Steppe of Ukraine have shown that when cultivating the winter wheat variety Khersonska bezosta, differences in productivity levels are observed depending on the plant protection systems against harmful organisms and seeding rates (Table 1). The highest grain yield in the experiment, at 6.52 t/ha, was obtained in the variant with plant protection

[457] Top 10 wheat producing countries in the world (2025). URL: https://ukragroconsult.com/en/news/top-10-wheat-producing-countries-in-the-world-2025/.

and a seeding rate of 5 million/ha. Seeding rates affected plant productivity differently. In the variant without plant protection, the highest yield of 5.61 t/ha was recorded at a seeding rate of 6 million/ha, while with plant protection and a seeding rate of 5 million/ha, the yield reached 6.52 t/ha.

1. Yield of winter wheat and grain quality depending on plant protection and seeding rates

Plant protection (factor A)	Seeding rate (factor B)	Grain yield, t/ha	Protein content, %	Gluten content, %
Without protection (water treatment)	4 million/ha	5.36	10.2	24.7
	5 million/ha	5.54	10.0	24.8
	6 million/ha	5.61	9.6	23.1
With protection (Vitavax 200 FF, 3.0 l/t; 2,4-D, 1.0 l/ha; Tilt, 0.5 l/ha; Bi-58 Novyi, 1.2 l/ha)	4 million/ha	6.13	13.0	28.5
	5 million/ha	6.52	11.6	26.8
	6 million/ha	6.30	10.9	25.2
LSD_{05}	A	0.18	0.08	0.24
	B	0.16	0.05	0.30
	AB	0.29	0.18	0.48

Source: author’s development.

Plant protection positively affected the protein content in wheat grain. The highest protein content was observed in the variant with plant protection at a seeding rate of 4 million/ha, reaching 9.3 %, while the lowest was 6.6 % in the variant without plant protection at a seeding rate of 5 million/ha.

2. Yield of winter wheat depending on sowing date and varietal composition

Sowing date (factor A)	Variety (factor B)					Average for factor A
	Khersonska bezoosta	Kokhana	Ovidiy	Erythrospermum 1936	Suputnytsia	
5.09	4.23	4.36	4.44	4.17	4.37	4.31
15.09	4.80	4.93	5.12	4.27	4.98	4.82
25.09	4.63	4.71	4.86	4.46	4.66	4.66
5.10	4.32	4.38	4.63	4.61	4.12	4.41
15.10	3.94	4.05	4.26	4.58	3.87	4.14
Average for factor B	4.38	4.49	4.66	4.42	4.40	4.47
$LSD_{0.5}$ (t/ha) for the factors: A – 0.23; B – 0.28; AB – 0.37						

Source: author’s development.

The duration of the periods “sowing – emergence” and “emergence – tillering” increased from the earliest to the latest sowing dates, whereas the periods from tillering to stem elongation and full grain maturity shortened. The studied varieties exhibited different responses to sowing dates. For example, the variety Erythrospermum 1936 had lower yields than all other varieties when sown on September 25, but when sown on October 15, it achieved the highest yield (4.58 t/ha), exceeding other varieties by 0.32–0.71 t/ha. The variety Ovidiy produced the highest yields of 5.12 and 4.86 t/ha when sown on September 15 and 25, respectively (Table 2).

The studied winter wheat varieties also showed differences in grain quality depending on the sowing date (Table 3). When sown on September 5, gluten content across the varieties ranged from 31.4 % to 32.8 %. Delaying sowing until October 15 slightly reduced this indicator to 25.7–30.9 %. All other parameters (glossiness, test weight, and hectoliter weight) remained practically the same across all sowing dates. Thus, based on the average results over the years of study, the optimal sowing period following a black fallow is between September 15 and 25.

3. Grain quality parameters of winter wheat depending on sowing date

Sowing date (factor A)	Variety (factor B)	Glassiness, %	Gluten content, %	GDI	Test weight, g/L
5.09	Khersonska bezoosta	61	31.4	80	738
	Kokhana	68	32.4	80	733
	Ovidiy	66	32.8	85	727
	Erythrospermum 1936	85	31.9	94	762
	Suputnytsia	63	32.4	80	733
5.10	Khersonska bezoosta	61	27.5	92	760
	Kokhana	65	30.4	83	740
	Ovidiy	65	30.5	81	745
	Erythrospermum 1936	86	32.0	95	763
	Suputnytsia	63	29.6	80	737
15.10	Khersonska bezoosta	65	25.7	75	760
	Kokhana	70	28.1	80	765
	Ovidiy	67	27.3	80	766
	Erythrospermum 1936	88	30.9	90	762
	Suputnytsia	61	29.1	95	746
$LSD_{0.5}$	A	2.5	1.9	1.8	5.6
	B	3.7	1.2	2.3	4.8
	AB	4.5	2.5	3.3	6.8

Source: author's development.

According to the analysis of stress tolerance of the studied winter wheat indicators, the lowest level (–1.11) was observed in the variety Suputnytsia, while in the other studied varieties it increased by 20.7–60.4 % (Table 4). Genetic flexibility reached its maximum (4.49–4.69) in the varieties Kokhana and Ovidiy. The coefficient of variation indicates a high variability of plant productivity depending on natural and agrotechnical factors, with the maximum variation of 34 % recorded in the variety Ovidiy. In terms of homeostaticity and breeding value, the advantage was found in the variety Erythrospermum 1936, while the lowest values were recorded in Suputnytsia.

4. Parameters of adaptability of the studied winter wheat varieties

Variety	Parameters				
	stress resistance $x_{lim} - x_{opt}$	genetic flexibility $(x_{lim} + x_{opt})/2$	V, %	H_{om}	S_c
Khersonska bezoosta	-0.69	4.37	29.2	65.6	3.59
Kokhana	-0.88	4.49	31.1	67.2	3.69
Ovidiy	-0.86	4.69	34.0	75.4	3.90
Erythrospermum 1936	-0.44	4.39	29.1	86.4	3.97
Suputnytsia	-1.11	4.43	30.2	40.4	3.44

Source: author's development.

In the course of the research, it was found that the uptake of nutrients occurs throughout the vegetation period and depends on the rate of above-ground biomass accumulation. Thus, the content of nitrate nitrogen in the soil changed during the vegetation period of the crop and significantly depended on the soil layer (Table 5).

5. Nitrate nitrogen content in the soil under winter wheat, mg/100 g of soil

Soil layer, cm	Plant development stage			
	emergence	heading	grain filling	milk ripeness
0–30	4.39	3.66	2.90	1.37
30–50	2.29	1.61	1.50	0.63
50–70	1.30	0.77	0.76	0.59
0–70	2.66	2.01	1.72	0.86

Source: author's development.

The nitrate content in the arable soil layer (0–30 cm) at the beginning of the winter wheat vegetation period (at emergence) averaged 4.39 mg/100 g of soil. With the start of irrigation during the vegetation period, by the heading stage and subsequently, the nitrate nitrogen content decreased in all experimental variants, which is associated with the uptake of this nutrient by the wheat plants for the formation of above-ground biomass. The intensity of growth processes and accumulation of above-ground mass particularly affected the consumption of this nutrient from the upper soil layers.

The average nitrate nitrogen content in the arable soil layer during the grain-filling stage was 21.9 % lower than during heading, and from heading to milk ripeness, this difference increased to 78.9 %. Thus, significant accumulation of above-ground biomass in irrigated winter wheat leads to a reduction in nitrate nitrogen content in the soil and decreased reserves for above-ground biomass formation. In the 0–70 cm soil layer, nitrate nitrogen content decreased from 2.66 to 0.86 mg/100 g of soil from emergence to milk ripeness, a 3.1-fold reduction.

The research results (Tables 6 and 7) also show that the content of available phosphorus and exchangeable potassium in the dark-chestnut soil before sowing was high, which is explained by the annual application of recommended NPK doses for all crops in the irrigated crop rotation.

6. Available phosphorus content in the soil under winter wheat, mg/100 g of soil

Soil layer, cm	Plant development stage			
	emergence	heading	grain filling	milk ripeness
0–30	6.55	6.27	4.86	3.40
30–50	2.22	1.44	1.32	1.22
0–50	4.39	3.86	3.09	2.18

Source: author’s development.

As observed, the accumulation of greater above-ground biomass contributed to more intensive use of available phosphorus. By the end of the vegetation period, the most intensive phosphorus uptake occurred from the 0–50 cm soil layer.

7. Exchangeable potassium content in the soil under winter wheat, mg/100 g of soil

Soil layer, cm	Plant development stage			
	emergence	heading	grain filling	milk ripeness
0–30	39.1	37.0	34.3	31.7
30–50	31.7	29.8	28.0	27.3
0–50	35.4	33.4	31.2	29.5

Source: author’s development.

The decrease in available phosphorus content in the 30–50 cm soil layer from heading to grain filling amounted to 24.8 %, and by the milk ripeness stage it reached 42.1 %. The most intensive reduction in available phosphorus occurred during the grain-filling phase. The high content of exchangeable potassium is explained by the characteristics of dark-chestnut soils in the arid conditions of the Steppe of Ukraine.

In the experiments, the initial reserves of exchangeable potassium in the arable layer and in the 0–50 cm soil layer remained practically unchanged during the early stages of growth and development and were sufficiently high, at 35.4 and 33.4 mg/100 g of soil, respectively. Subsequently, during the vegetation of winter wheat, the content of exchangeable potassium in the 0–50 cm soil layer decreased by 5.6–7.2 %. The most intensive uptake of exchangeable potassium by winter wheat occurred during the grain-filling period.

Thus, throughout the vegetation period, as winter wheat plants grew and developed, the content of key nutrients in the soil decreased. Changes in seeding rates and plant protection had little effect on nitrogen, phosphorus, and potassium removal from the soil, which primarily depended on the plant development stage and soil depth.

At the time of emergence, the moisture content of the 2-meter soil layer in the experimental plots averaged 83.5 %, at the onset of winter – 73.7 %, and at the resumption of vegetation – 83.4 % of field capacity. Therefore, starting from the second half of the vegetation period, a reduction in productive water reserves was noted, especially in the upper 0–50 cm soil layer (Table 8).

8. Dynamics of productive water reserves and moisture deficit in winter wheat, m³/ha, average across the studied factors

Phase	Productive water in the soil layer, cm		Soil moisture deficit in the soil layer, cm	
	0–50	0–100	0–50	0–100
Emergence	667	1056	267	635
Wintering	652	1000	281	691
Resumption of vegetation	752	1309	182	381
Stem elongation	347	887	587	804
Heading	184	410	849	1280
Milk ripeness	156	183	899	1507
Full ripeness	133	151	970	1606

Source: author’s development.

Observations of water evaporation during the interphase periods of winter wheat development for the variety Khersonska bezosta showed that the average daily water loss from the 0–100 cm soil layer during the period from vegetation resumption to stem elongation was 25.9 m³/ha per day. Subsequently, from the stem elongation to heading stage, the average daily evaporation increased to 42.7 m³/ha. The maximum value was observed during the interphase period from heading to milk ripeness, reaching 61.2 m³/ha. Afterwards, a decrease in average daily evaporation was noted, down to 23.9 m³/ha, or 2.6 times lower.

Development of elements of winter barley cultivation technology. By summarizing five years of field studies with winter barley varieties, the influence of crop protection on grain yield was established. During the study years, the highest grain productivity was recorded under favorable conditions in 2009 for the varieties Dostoyny (6.21 t/ha) and Zymovyi (6.44 t/ha). Due to the adverse effects of drought and rainfall deficit in 2008, yields in the unprotected variant decreased for the Zymovyi and Trudivnyk varieties to 3.27–3.29 t/ha. Yield further declined under severe drought conditions in 2012, with the Aborygen (3.21 t/ha) and Taman (3.27 t/ha) varieties showing the lowest productivity.

On average, over the years of research, both in the unprotected and protected variants, the highest yields were obtained from the Dostoyny variety – 4.50–5.13

t/ha. The lowest results in unprotected plots were recorded for the Taman and Aborygen varieties – 3.92–3.94 t/ha, while in the protected plots the lowest yields were observed for Metelytsia, Rosava, and Trudivnyk – 4.42, 4.45, and 4.46 t/ha, respectively. Thus, the difference between the best and worst-performing varieties in unprotected variants ranged from 4.5 % to 14.8 %, while in protected plots it ranged from 5.2 % to 16.1 %. On average, factor A demonstrated the advantage of crop protection, increasing winter barley grain yield from 4.12 to 4.65 t/ha, or by 12.9 %.

Statistical analysis showed that stress-resistance indicators were minimal (–0.35) for the Metelytsia variety (Table 9). For the last three varieties studied – Taman, Dostoyny, and Aborygen – this indicator increased by 41.7–49.3 %, reaching –0.60, –0.63, and –0.69, respectively.

9. Adaptive parameters of the studied winter barley varieties

Variety	Parameters				
	Stress resistance $x_{lim} - x_{opt}$	Genetic flexibility $(x_{lim} + x_{opt})/2$	V, %	H_{om}	S_c
Rosava (st)	–0.43	4.23	18.6	53.1	3.82
Metelytsia	–0.35	4.25	21.9	56.3	3.92
Zymovyi	–0.56	4.59	25.0	34.0	4.07
Trudivnyk	–0.44	4.24	15.6	61.7	3.82
Osnova	–0.52	4.46	15.4	57.0	3.97
Taman	–0.69	4.28	18.2	34.2	3.64
Aboryhen	–0.60	4.23	21.5	33.0	3.66
Dostoinyi	–0.63	4.81	19.0	49.1	4.22

Source: author's development.

Genetic flexibility increased to 4.81 in the variety Dostoyny, while in the varieties Rosava and Aborigen it decreased to 4.23, or by 12.1 %. The coefficient of variation decreased to 15.4–15.6 % (medium level of variability) in the varieties Trudivnyk and Osnova. In the variety Zymovyi, this indicator increased to 25.0 %, indicating high variability in grain yield of the studied crop. Homeostasis (Hom) was highest in the variety Trudivnyk – 61.7, whereas in the varieties Aborigen, Zymovyi, and Taman it decreased to 33.0–34.2, or by 44.6–46.5 %. The maximum selection value (Sc) was observed in the varieties Dostoyny – 4.22 and Zymovyi – 4.07, while the lowest result was in the variety Taman – 3.64, which is 10.6–13.8 % lower than the first two varieties. The quality of winter barley grain, depending on the use of crop protection, was studied using two indicators – protein content and starch content (Table 10).

It was established that the protein content in the grain of the studied barley varieties, grown without plant protection, exceeded 10 % in the varieties Zymovyk and Trudivnyk, while in the grain of the varieties Aboryhen and Dostoynyy it decreased to 9.3–9.4 %. The application of plant protection measures resulted in an increase in protein content across all varieties by 0.5–1.0 %, except for the Zymovyy variety, where this indicator decreased by 0.2 %.

10. Winter barley grain quality depending on crop protection application

Protection (factor A)	Variety (factor B)	Content, %			
		protein	± from protection	starch	± from protection
Without protection	Rosava (st)	9.6	–	52.8	–
	Metelytsia	9.7	–	51.7	–
	Zymovyi	10.2	–	53.1	–
	Trudivnyk	10.6	–	52.8	–
	Osnova	9.5	–	51.5	–
	Taman	9.5	–	51.2	–
	Aboryhen	9.3	–	51.6	–
	Dostoinyi	9.4	–	51.2	–
Average for factor A		9.7	–	52.0	–
With plant protection	Rosava (st)	10.3	0.7	49.6	–3.2
	Metelytsia	10.3	0.6	50.2	–1.5
	Zymovyi	10.0	–0.2	52.6	–0.5
	Trudivnyk	10.9	0.4	50.8	–2.0
	Osnova	10.6	1.0	50.7	–0.7
	Taman	10.1	0.6	52.7	1.5
	Aboryhen	10.3	1.0	52.3	0.6
	Dostoinyi	9.9	0.5	54.6	3.3
Average for factor A		10.3	–	51.7	–
LSD_{05}	A	0.23		0.75	
	B	0.16		0.59	

Source: author’s development.

On average, across all varieties, a slight increase in protein content in winter barley grain was observed, from 9.7 % (without plant protection) to 10.3 % (with plant protection).

The starch content in the grain of the studied crop generally showed opposite trends. In the variants without plant protection, this indicator was 52.0 %, while in the variants with protection it slightly decreased to 51.7 %, or by 0.6 %.

It should be noted that in the varieties Rosava, Metelytsia, Zymovyy, Trudivnyk, and Osnova, starch content decreased by 0.5–3.2 %. Conversely, in the varieties Aboryhen, Taman, and Dostoynyy, this indicator increased by 0.6–3.3 %.

Ecologization of spring barley cultivation technology elements under the conditions of the Steppe of Ukraine. In recent years, the use of various chemical agents in agricultural production has been increasing. As is known, these substances can enter food, water, and air, negatively affecting human health. This situation encourages the search for alternative means of natural biological origin that do not harm the environment or society. A pressing issue in modern production is the development of biological preparations that contribute to increased grain yields while remaining environmentally safe and harmless to human health. Particular attention is paid to substances used for activating and stimulating seed material, as well as for improving the conditions for plant growth and development. An important aspect of modern biopreparations is their ability to enhance plant resistance to various diseases. The data obtained in our experiments (Table 11) indicate the significant effectiveness of biopreparations in the treatment of seeds of spring barley varieties.

11. Field germination of spring barley seeds depending on their treatment with biopreparations, %

Biopreparation	Variety	
	Dostoynyy	Galaktik
Control	54.4	61.2
FMB	57.9	61.1
Polymixobacterin	56.6	62.8

Source: author’s development.

It was determined that the field germination of seeds of both spring barley varieties slightly increased due to their treatment with biopreparations. In particular, for the Dostoynyy variety, the best results were achieved with pre-sowing seed bacterization using FMB, which exceeded the control by 6.0 % and the Polymixobacterin treatment by 2.2 %. Conversely, for the Galaktik variety, seeds treated with Polymixobacterin showed the highest field germination, 2.5 % higher than the control and 2.7 % higher than the FMB inoculation. Therefore, it can be concluded that both biopreparations and the varietal characteristics of spring barley influence field germination.

Phenological observations showed that seedlings emerged simultaneously in all experimental variants. No differences were found in the timing of the main developmental phases of the plants. The analysis of the accumulated data from our studies indicates that seed inoculation with microbiological preparations led to a noticeable increase in some biometric indicators, particularly plant height. When sowing seeds inoculated with microbiological preparations, plants were slightly taller compared to the control variant (Table 12). The analysis of the table data indicates that several factors influenced plant height: microbiological preparations, varietal characteristics, and the developmental phase of the crop.

It should be noted that the application of each of the studied preparations had a positive effect on plant height. However, compared to the control, the greatest increase in spring barley plant height was achieved with the use of FMB. The effective influence of this biopreparation on height was already observed at the beginning of tillering, whereas with the application of Polymixobacterin (during this period), only a tendency for an increase in this indicator was noted. During the heading period, the differences in height between the variants became more pronounced, but it was not possible to establish a clear advantage of any of the studied preparations.

12. Height of spring barley plants of different varieties depending on seed treatment with microbiological preparations, dm

Biopreparation	Variety			
	Dostoynyy		Galaktik	
	Plant development phase			
	tillering	heading	tillering	heading
Control	2.94	6.4	2.82	6.47
FMB	3.16	6.6	3.18	6.67
Polymixobacterin	3.1	6.5	3.06	6.61

Source: author’s development.

In addition to plant height, microbiological preparations also positively affected the tillering capacity of the plants (Table 13). The data analysis indicates that plants from seeds treated with biopreparations exhibited better tillering and produced a greater number of productive stems compared to the control variants. The highest coefficients of total and productive tillering were observed in plants whose seeds were inoculated with FMB before sowing.

13. Effect of microbiological preparations on tillering capacity of spring barley plants of different varieties, pcs./plant

Biopreparation	Variety			
	Dostoynyy		Galaktik	
	Plant development phase			
	tillering	heading	tillering	heading
Control	1.5	1.4	1.5	1.5
FMB	1.8	1.7	1.8	1.7
Polymixobacterin	1.7	1.5	1.7	1.6

Source: author’s development.

Another studied preparation also positively influenced the tillering process, but its effectiveness was lower; for instance, during the tillering phase, it exceeded the control by 11.8 % but was 5.6 % lower than the FMB treatment. When comparing the tillering capacity of the studied varieties, Galaktik plants tillered more intensively than Dostoynyy plants, whereas the latter showed more vigorous tillering under the influence of biopreparations.

It is important to note that, similar to tillering capacity, the leaf area of spring barley plants also changed accordingly (Table 14).

Pre-sowing seed treatment with microbiological preparations contributed to the development of a more extensive assimilative surface in the plants, regardless of the variety. However, the best results were achieved with seed inoculation using FMB bacterial strains. It should be noted that the difference in leaf area between the control and the treated variants was already quite pronounced at the beginning of the tillering phase and persisted until the end of the plant’s vegetation period. It should also be emphasized that Galaktik plants formed a larger assimilative surface compared to Dostoynyy plants. One of the main factors affecting the formation of fully developed tillering shoots, the subsequent retention of a greater number of productive stems, and the development of a better leaf area in spring barley is the degree of development of the secondary root system (Table 15).

14. Leaf area of spring barley plants depending on seed treatment with microbiological preparations, dm²

Biopreparation	Variety			
	Dostoynyy		Galaktik	
	Plant development phase			
	tillering	heading	tillering	heading
Control	0.35	0.46	0.37	0.47
FMB	0.39	0.51	0.40	0.52
Polymixobacterin	0.37	0.50	0.39	0.51

Source: author’s development.

The data analysis indicates that the number of nodal roots formed by spring barley plants increased under the influence of microbiological preparations. The highest number of nodal roots was observed in plants whose seeds were treated with the preparation based on nitrogen-fixing bacteria FMB.

15. Formation of the secondary root system in plants of different barley varieties under the influence of microbiological preparations, pcs./plant

Biopreparation	Variety			
	Dostoynyy		Galaktik	
	Plant development phase			
	tillering	heading	tillering	heading
Control	2.1	3.9	2.6	4.3
FMB	2.7	5.1	3.2	5.0
Polymixobacterin	2.3	4.4	2.9	4.3

Source: author’s development.

It is also noteworthy that biopreparations were particularly effective in promoting the formation of the secondary root system in spring barley during the stem elongation to heading period. Compared to the tillering phase, the effect of biopreparations on secondary root system development became more pronounced. Among the two studied barley varieties, Galaktik had a greater number of nodal roots; however, the application of microbiological preparations more effectively stimulated the development of the secondary root system in the Dostoynyy variety.

Moreover, under the influence of biopreparations, barley plants formed slightly more nodal roots already at the beginning of tillering, whereas in the control, they appeared as small bulges or protuberances. Later, during the heading period, after late rainfall, the application of microbiological preparations contributed to the formation of additional nodal roots compared to the control in both studied varieties.

From this analysis, it follows that the use of microbiological preparations increased the biomass of both the aboveground parts and the root system of barley plants, which was already recorded at the beginning of tillering. A similar, but more pronounced, trend was observed during the heading period (Table 16).

16. Dry biomass of aboveground parts and root system of barley varieties depending on biopreparations at the heading stage, t/ha

Variety	Biopreparation	Root system biomass in the 0–120 cm	Aboveground biomass
Dostoynyy	Control	1.53	6.85
	FMB	1.83	7.07
	Polymixobacterin	1.63	6.99
Galaktik	Control	1.76	6.95
	FMB	2.00	7.62
	Polymixobacterin	1.88	7.26

Source: author’s development.

During this period, a significant increase in both aboveground biomass and root system biomass under the influence of biopreparations was observed in almost all variants compared to the control. It is important to note, however, that the effect of biopreparations on the formation of these biometric indicators in barley plants was not uniform.

Specifically, pre-sowing seed bacterization with FMB resulted in plants with the largest habitus and root system. In particular, the dry aboveground biomass of the Dostoynyy variety was 3.1 % higher than the control, while in Galaktik it was 8.8 % higher. The root system biomass of Dostoynyy plants in the 0–120 cm soil layer exceeded the control by 16.4 %, and that of Galaktik by 12.0 %.

In our opinion, the degree of development of the barley root system can be assessed using the root-to-shoot ratio, which reflects the quantitative relationship between the mass of the root system and the vegetative part (Table 17).

17. Root-to-shoot ratio of spring barley varieties under the influence of microbiological preparations at the heading stage, %

Biopreparation	Variety	
	Dostoynyy	Galaktik
Control	22.3	25.4
FMB	25.8	26.3
Polymixobacterin	23.3	25.9

Source: author’s development.

Inoculation of seeds with biopreparations contributed to an increase in the root-to-shoot ratio of plants, and this effect was consistently observed in both studied varieties. It should be noted that a significant increase in root-to-shoot ratio in Dostoynyy and Galaktik plants was particularly evident with pre-sowing seed bacterization using FMB.

It should also be noted that in the variant where Galaktik seeds were treated with Polymixobacterin, the root-to-shoot ratio of plants did not differ significantly from the control, although the total aboveground and root biomass increased. This pattern was observed throughout all years of the study. We believe this can be explained by an increase in the absorptive capacity of the root system under the influence of Polymixobacterin, which allows it to function more efficiently even with a smaller root volume.

We consider it important to emphasize that inoculation with microbiological preparations had a more pronounced positive effect during the heading–flowering period, whereas during the tillering phase, plant development under the influence of biopreparations improved only slightly. This is likely due to the initially low population of bacteria in the preparations at the early stages of plant development, although they begin functioning immediately upon entering the soil with the seed. These bacteria rapidly multiply, forming new colonies in the rhizosphere, interact with other soil microorganisms, and, most importantly, perform nitrogen fixation and mobilization of poorly available phosphates. Therefore, during heading, when the bacterial population significantly increases, they play an important role in providing plants with essential nutrients.

Increasing the efficiency of chemical inputs applied at minimal doses is possible through maximum utilization of biological factors. Seed inoculation with microbiological preparations allows plants to meet their nutrient needs with smaller amounts of nitrogen and phosphorus fertilizers. However, the effect of seed inoculation on nitrogen uptake from the soil by barley plants had not previously been studied.

Data obtained from 2010–2012 indicate that seed inoculation with biopreparations influenced nitrogen uptake from the soil and its utilization per unit of yield, although the variability of these indicators differed across years.

In 2010, nitrogen uptake per unit of yield and total nitrogen removal from the soil under biopreparation treatments largely depended on the response of the studied varieties. Seed treatment with FMB increased nitrogen removal in almost all experimental variants, while on plots treated with Polymixobacterin, the values remained at control levels. Analysis of nitrogen use by plants in 2010 showed that the highest values for both barley varieties were observed with FMB inoculation.

In 2011, seed inoculation with microbiological preparations increased nitrogen use per unit of yield for both barley varieties. It is important to note that nitrogen removal from the soil and its use per ton of grain moderately increased under FMB treatment.

The effect of microbiological preparations on total nitrogen removal and nitrogen use per unit of yield in 2012 was similar to that in 2011. These indicators increased in almost all experimental variants. This phenomenon is likely explained by the lower grain and straw yields in 2012, resulting in a smaller proportion of nitrogen being used for biomass formation and a lower total nitrogen removal from the soil.

Summarizing the data across years, seed inoculation with microbiological preparations increased nitrogen removal from the soil and nitrogen use per ton of yield in both studied varieties.

When comparing varieties, total nitrogen removal was higher in Galaktik than in Dostoynyy, while Galaktik plants also showed higher grain productivity.

It is well known that the main criterion objectively reflecting the effectiveness of an agricultural practice is grain yield. At the current stage of agricultural development, pre-sowing inoculation of spring barley seeds with microbiological preparations is considered one of the latest technological practices capable of enhancing the adaptability of barley plants to environmental stress factors, including high temperatures and insufficient water availability. Analysis of spring barley grain yield variability under the influence of biopreparations over the study years showed that their effect largely depended on certain factors, such as varietal characteristics and weather conditions.

Summarizing the yield data from our field experiments, we established that the use of microbiological preparations positively affected plant productivity (Table 18). Thus, on average over the three years of the study, the grain yield of spring barley was higher in the Galaktik variety when treated with FMB, reaching 2.94 t/ha, which exceeded the control by 1.72 t/ha. Application of Polymixobacterin provided an increase of 1.67 t/ha. It is also noteworthy how the studied varieties responded to microbiological preparations. It was found that Dostoynyy plants exhibited a more pronounced response to the applied biopreparations, resulting in a significant increase in grain yield. We believe that this response in Dostoynyy was related to the development level of the root system.

Plants of this variety had less developed primary and secondary root systems, which were unable to fully meet the nutrient requirements of the plants, especially in the drought year of 2012. Therefore, the use of microbiological preparations substantially improved root system development in Dostoynyy plants, allowing them to utilize additional nutrients generated through enhanced nitrogen fixation and phosphate mobilization.

This phenomenon is confirmed by the significant yield increase observed for this variety. At the same time, it should be noted that in each individual year of the study, the response of the varieties to the biopreparations varied: in one year, Dostoynyy showed a higher yield increase, while in another, Galaktik had the advantage. Interestingly, the Galaktik variety consistently exceeded Dostoynyy in yield across all years and in each seed bacterization variant. For example, with FMB treatment, the grain yield of Galaktik was 0.05 t/ha higher than that of Dostoynyy.

18. Grain yield of spring barley varieties depending on seed inoculation with microbiological preparations

Biopreparation	Variety			
	Dostoynyy		Galaktik	
	yield, t/ha	increase compared to control, t/ha	yield, t/ha	increase compared to control, t/ha
2010				
Control	1.18	-	1.23	-
FMB	2.98	1.80	3.02	1.79
Polymixobacterin	2.76	1.58	2.94	1.71
2011				
Control	1.22	-	1.25	-
FMB	2.93	1.71	3.00	1.75
Polymixobacterin	2.85	1.63	2.97	1.72
2012				
Control	1.15	-	1.17	-
FMB	2.76	1.61	2.81	1.64
Polymixobacterin	2.64	1.49	2.77	1.60
Average for 2010–2012				
Control	1.18	-	1.22	-
FMB	2.89	1.71	2.94	1.72
Polymixobacterin	2.75	1.57	2.89	1.67
LSD_{05}, t/ha (2010): A – 0.165; B – 0.071; AB – 0.172. LSD_{05}, t/ha (2011): A – 0.208; B – 0.141; AB – 0.197. LSD_{05}, t/ha (2012): A – 0.078; B – 0.064; AB – 0.093.				

Source: author's development.

Therefore, the yield data analysis allows us to conclude that the use of microbiological preparations for spring barley seed inoculation is an effective method to increase plant productivity, providing yield gains even under conditions of elevated air and soil drought.

Analysis of the effect of microbiological preparations on grain quality over the years showed a significant impact on grain protein content. On average, from 2010 to 2012, in Dostoynyy barley, pre-sowing treatment with FMB increased protein content by 2.2 and 5.6 percentage points compared to Polymixobacterin treatment and the control, respectively (Table 19). At the same time, starch content increased by 0.3 and 1.2 percentage points, respectively.

Similarly, the biopreparations affected the protein and starch content in the grain of the Galaktik variety. In this case, the protein content in the uninoculated control was 0.5 % lower compared to the FMB treatment and 0.3 % lower than with Polymixobacterin treatment. At the same time, the starch content in Galaktik grain increased compared to the control by 2.1 % with FMB and by 0.9 % with Polymixobacterin.

19. Biochemical composition of spring barley grain varieties depending on pre-sowing seed bacterization

Biopreparation	Protein content in grain, %		Starch content in grain, %	
	Variety			
	Dostoynyy	Galaktik	Dostoynyy	Galaktik
Control	8.5	8.4	58.2	57.7
FMB	9.0	8.9	58.9	59.8
Polymixobacterin	8.8	8.7	58.7	58.6

Source: author's development.

Thus, the results of the study indicate that the formation of quality traits in spring barley grain is influenced by several factors, including varietal characteristics and seed inoculation with microbiological preparations.

In our opinion, special attention should be given to the morpho-genetic traits of barley varieties. It was also found that annual weather conditions and the studied measures affected the quality traits in the grain of Dostoynyy, whereas in Galaktik, the protein and starch content remained stable. This can be explained in several ways. First, throughout the study years, the grain yield of Galaktik was higher compared to Dostoynyy, although the quality traits of Dostoynyy grain changed less significantly. The second and main reason lies in the breeding characteristics of the varieties. Since Dostoynyy is a feed-type barley, breeders focused primarily on enhancing plant adaptability to extreme weather conditions and achieving higher productivity. Galaktik, being a malting barley, was bred with an emphasis on improving brewing qualities, particularly protein and starch content in the grain, which are genetically controlled and heritable.

Ecological aspects of cultivating field pea. Currently, the trend of middle-class consumption, which is already characteristic of developed countries and is rapidly growing in China, India, and other developing countries, is gaining increasing popularity worldwide. This means that the number of people seeking to consume high-quality and healthy food is increasing. A similar trend is observed in Ukraine. Accordingly, there is growing demand for food products with added consumer value – organic products, bioproducts, farm products, superfoods, fitness foods, and other healthy foods, based on niche production. According to domestic scientists and market analysts, niche crops can significantly diversify the grain-oilseed sector, reduce the dominance of sunflower and rapeseed in crop rotations, the cultivation of which beyond normative limits greatly depletes the topsoil. Therefore, it is important to develop underutilized niche crops using principles of biologization and innovative resource optimization. Among niche crops, peas hold a significant position.

The production of plant protein has always been a key issue in agriculture. Plant protein is the most important component of food and feed resources, the use of which significantly affects human health, well-being, life expectancy, and quality of life. This is especially important now, given the significant growth of the world population, which has led in some countries to protein deficiency. In recent years, plant protein accounted for 70 % of the total protein balance. The average protein consumption per capita in Ukraine is 82.4 g/day, in developed countries – 99.4 g/day, in developing countries – 69.6 g/day, and in less developed countries – 58.1 g/day. Considering this, the demand for high-protein plant raw materials is constantly increasing, and prices for them are significant on both global and domestic markets.

Leguminous crops are also important for stabilizing and enhancing soil fertility by replenishing soil nitrogen through biological fixation. Including them in crop rotations promotes higher yields of main grain crops and strengthens the financial position of producers. This led to a 12.5 % increase in global legume production between 1995 and 2015. Unfortunately, in Ukraine, mainly due to economic and organizational issues, production has significantly decreased.

Pea is a high-yield, valuable food and feed crop, with seeds characterized by high protein content. Moreover, it is a valuable concentrated feed for livestock. Such multifunctional use requires the creation of specialized varieties for different purposes of seed use and ensures that these varieties have the necessary specific combinations of biochemical and technological traits. The global pea cultivation area is approximately 8 million ha, with large areas in Canada (1.1 million ha) and China (0.75 million ha). It is also grown in the UK, Sweden, the Netherlands, Belgium, and other countries. In Ukraine, peas occupy about 0.5 million ha with an average yield of 2.7 t/ha, with significant areas in Vinnytsia, Khmelnytskyi, Cherkasy, Kyiv, Chernihiv, and Sumy regions. At the Institute of Irrigated Agriculture of the NAAS, a pea cultivation technology adapted to the arid conditions of the Southern Steppe has been developed, ensuring yields of 2.4–4.1 t/ha depending on moisture conditions. This technology includes optimizing seeding rates of modern varieties, levels of mineral and micronutrient fertilization, and crop protection from harmful organisms (weeds, pests, diseases). The cultivation of different pea varieties allowed determining that yield structure indicators vary depending on crop protection schemes. For example, pod length slightly increased up to 6.3 cm in the Devis variety under chemical and integrated protection. The number of pods per plant and seeds per pod also changed slightly, reflecting the trends mentioned above (Table 20).

The seed weight per plant, on average across varieties, was highest in the Devis variety – 3.9 g. For the Otaman variety, this productivity indicator was 3.3 g, i.e., 18.9 % lower. It was found that the seed weight per plant of Devis slightly increased under chemical and integrated crop protection. Maximum yield was recorded for the Devis variety under chemical – 2.54 t/ha and integrated – 2.68 t/ha crop protection. In the control variant with the Otaman variety, this indicator decreased to 1.78 t/ha, i.e., 1.4–1.5 times lower.

20. Yield and grain quality of pea depending on varietal composition and plant protection, t/ha

Variety (factor A)	Crop protection (factor B)	Yield, t/ha	Content, %		
			crude protein	crude fat	crude fiber
Otaman	No protection	1.78	18.3	1.37	1.66
	Chemical	2.08	19.3	1.65	1.79
	Biological	1.96	18.9	1.59	1.58
	Integrated	2.14	19.8	1.71	1.63
Devis	No protection	2.18	19.1	1.15	1.72
	Chemical	2.54	21.0	1.35	2.10
	Biological	2.11	20.4	1.28	1.68
	Integrated	2.68	21.7	1.41	1.92
LSD_{05}	A	0.08	0.55	0.07	0.06
	B	0.03	0.41	0.05	0.04
	AB	0.11	0.75	0.12	0.14

Source: author’s development.

It has been proven that plant protection contributes to an increase in crude protein content in pea grain: in the Otaman variety by 0.5–1.5 %, and in the Deviz variety by 0.7–2.6 %, with the integrated plant protection scheme combining chemical and biological preparations showing the greatest effectiveness. The crude fat content was higher in the Otaman variety. The maximum crude fiber content (2.1 %) was recorded in the Deviz variety under chemical plant protection.

Development of agrotechnical measures for cultivating phytoenergetic crops on the principles of ecologization. There is a growing global interest in the use of renewable energy sources, particularly plant-based raw materials, due to price instability and the limited reserves of fossil fuels. It is projected that the share of biofuels in global fuel consumption will reach 7–10% in the coming years. Ukraine, whose energy sector largely depends on imported resources, is also interested in developing alternative sources. The production of bioethanol, biodiesel, and biogas is becoming a priority worldwide. In 2012, there were 738 ethanol plants with a total capacity of 123.5 million tons. The leading producers of bioethanol are the USA, Brazil, and China, which reflects the global trend toward energy diversification.

Due to the anticipated depletion of the main fossil energy resources within the next 40–50 years, the use of renewable energy sources has become one of the most pressing issues both worldwide and in Ukraine. Investments in the development of technologies for obtaining energy from renewable sources, such as solar, wind, water, biomass (organic materials of plant or animal origin), and geothermal energy, have become an urgent necessity. Therefore, one of the tasks of innovative agriculture is to increase sustainable production of biomass, biofuels, and other forms of renewable energy to implement the “green” transition, as outlined in the *Concept of the Green Energy Transition of Ukraine until 2050*.

Bioenergy involves the production of energy from biomass, that is, from organic materials of plant or animal origin. This energy can be obtained through various processes such as combustion, fermentation, or gasification. Bioenergy includes such forms of energy as biofuels (for example, biodiesel or ethanol), biogas produced from organic waste, as well as electricity generated from the biomass of phytoenergy crops.

Phytoenergy crops are cultivated specifically for energy production. They are selected to have high energy value and fast regeneration, which makes them ideal as raw materials for biomass. These crops may include both annual and perennial plants. Phytoenergy crops are an important element of the energy transition since they enable the production of renewable energy, reduce greenhouse gas emissions, and contribute to the sustainable development of agriculture.

Currently, research focuses on fast-growing energy plants suitable for producing organic biomass. Such crops include annual and perennial herbaceous plants such as sweet sorghum, Jerusalem artichoke, cup plant (*Silphium perfoliatum*), sugarcane, miscanthus, amaranth, knotweed (*Polygonum cuspidatum*), Sakhalin knotweed, Pennsylvania mallow, *Rumex*, switchgrass, hybrid tobacco, as well as fast-growing trees such as various species of willow and poplar, and paulownia.

Modern technologies of biofuel energy production are aimed at reducing negative environmental impacts, increasing productivity and return on investment, and mitigating competition for land resources with food and feed crops by enabling cultivation on marginal lands.

The study by Orekhivskyi et al. (2022) [458] demonstrated the high effectiveness of using organo-mineral biopreparations in chickpea cultivation, which can also be adapted to other niche crops, including lavender and sorghum, considering the similar agro-climatic conditions of Southern Ukraine.

The research by Kovalenko, Chernova, and Kutnyakh (2018) [459] examines varietal characteristics and sowing density as key factors influencing the yield of sweet sorghum under irrigation in Southern Ukraine. The results showed that a properly selected seeding rate and variety can ensure a significant increase in green mass yield, which is important both from an agronomic and an economic perspective. The authors note that sorghum exhibits high adaptability to drought conditions and holds promise as both an energy and fodder crop, enhancing its competitiveness among niche crops.

Bazaluk et al. (2021) [460] conducted an energy assessment of sorghum cultivation in southern Ukraine under climate change conditions. Field

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[458] Efficiency of using organo-mineral biopreparations as elements of biologization in chickpea cultivation technologies in the arid southern steppe of Ukraine / V. Orekhivskyi et al. *International Journal of Ecosystems and Ecology Science*. 2022. Vol. 12 (4). doi: 10.31407/ijees12.403

[459] Kovalenko O., Chernova A., Kutnyakh L. Productivity of sweet sorghum depending on sorts features and different of seed rates in native irrigation conditions of the Southern Ukraine. *Scientific Horizons,* 2018. Vol. 7–8 (70). P. 64–71. doi: 10.33249/2663-2144-2018-70-7-8-64-71

[460] Bazaluk O., Havrysh V., Fedorchuk M., Nitsenko V. Energy assessment of sorghum cultivation in southern Ukraine. *Agriculture (Switzerland).* 2021. Vol. 11 (8), Article 695. doi: 10.3390/agriculture11080695

experiment results demonstrated that with annual precipitation around 350 mm, it is possible to harvest up to 40.6 t/ha of green sorghum biomass, indicating the crop's high adaptability to arid environments. The study identified mineral fertilizers as the main contributors to energy input (56.99 %). The energy efficiency coefficient for sweet sorghum reached 11.18, while for grain sorghum it ranged from 2.8 to 16.7. These findings confirm both the agronomic and economic feasibility of cultivating sorghum as a niche crop with significant potential for bioenergy applications.

Sorghum is a widely cultivated crop grown in more than 85 countries across the world. Among cereal crops, sorghum ranks fifth in terms of global production volume. The largest cultivation areas are concentrated in Africa and Asia, where this crop serves as a staple food for more than 200 million people. In addition to its role in human nutrition, sorghum is also extensively used as livestock feed and as a raw material for biofuel production. Given the rapid global warming trends, there is an increasing need to shift agricultural production towards more drought-tolerant crops, among which sorghum holds a prominent position. This crop demonstrates a high degree of adaptability to diverse soil and climatic conditions, including arid environments. However, sorghum also responds positively to irrigation – even minimal irrigation rates can lead to a substantial increase in yield. Incorporating sorghum into crop rotations contributes to reducing nematode populations. Extending crop rotation cycles, diversifying crop species, and maintaining a balance between winter and spring crops are effective strategies for weed control. The use of sorghum as a preceding crop for spring species such as sunflower, pea, and soybean provides an ecologically and agronomically sound approach to crop rotation management. Nevertheless, the primary disadvantage of sorghum as a preceding crop is the potential risk of *Fusarium* infection in subsequent wheat plantings. The disease may develop around sorghum stems, and the pathogen can persist on crop residues from year to year. Sorghum is primarily cultivated in the southern, warmer regions of Ukraine and Kazakhstan, mainly for technical or industrial purposes. However, sorghum possesses excellent nutritional properties and high energy value. Sorghum flour is used in baking bread, confectionery, and in the production of baby food [461].

As of 2025, the leading sorghum grain producers are the United States, Nigeria, Brazil, India, Mexico, Ethiopia, Sudan, China, Argentina, and Australia. Among all producing countries, the United States accounts for the largest share of global sorghum production – approximately 21 %. The largest sorghum cultivation area is recorded in Sudan (6.00 million hectares), while the highest grain yield, averaging 4.76 t/ha, was achieved in China in 2025 [462]. In Ukraine, both the cultivated area and grain yield of sorghum have

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[461] Baklanova T. V., Hamaiunova V. V., Sydiakina O. V. Modern Trends in Sorghum Cultivation in Ukraine and Worldwide. *Tavriya Scientific Bulletin*. 2023. No. 134. P. 9–17. doi: 10.32782/2226-0099.2023.134.2

[462] The Foreign Agricultural Service (FAS) links U.S. agriculture to the world to enhance export opportunities and global food security. URL: https://www.fas.usda.gov/

shown a steady decline. The use of varieties and hybrids adapted to specific soil and climatic zones is a prerequisite for improving yield potential and increasing total grain production of sorghum.

According to our previous studies, the N:C ratio in straw is 1:73, with nitrogen content of 0.51 % and carbon content of 37.48 %. Phosphorus content in straw was 0.25 %. The total nitrogen in wheat straw remaining after harvest under plowing was 29.6 kg/ha, under chisel tillage – 27.8 kg/ha, and under shallow non-inversion tillage – 25.4 kg/ha. Carbon content in straw was 2,178, 2,041, and 1,866 kg/ha, respectively.

The post-harvest period was characterized by high air temperatures, with irregular precipitation in the region, which was not always favorable for the effective activity of straw-decomposer preparations. Nevertheless, their application significantly increased the rate of straw and residue decomposition compared to untreated controls.

The highest decomposition of straw 90 days after treatment was achieved with Ecostern – 66.2 %, which exceeded the control by 31.4 %. Organic Balance also showed high effectiveness, decomposing 63.4 % of wheat straw. The slowest decomposition occurred with Biodestroyer of Straw and Cellulose Destroyer, which resulted in 58.6 % and 56.4 % decomposition, respectively.

The decomposition rate was also significantly influenced by the method and depth of tillage, as it affected the incorporation depth of post-harvest residues and the resulting soil moisture conditions in the residue layer. In the control variant without microbial treatment, replacing plowing with non-inversion tillage at the same depth reduced decomposition by 3.4 %, while shallow non-inversion tillage reduced it by 7.6 %. On average, deep non-inversion tillage reduced decomposition by 9.4 %, and shallow tillage by 18.1 %. In the No-till system, treating unincorporated wheat residues with decomposer preparations reduced straw decomposition intensity to 42.6–46.7 %.

The application of microbial preparations also influenced soil biological activity under the subsequent crop of grain sorghum. The transformation of organic matter from wheat post-harvest residues under microbial treatments increased the number of microorganisms involved in nitrogen transformation processes. For example, ammonifying microorganisms in the arable layer at the beginning of sorghum vegetation increased by 1.66–5.80 million/g under plowing compared to untreated variants. The highest number of these microorganisms was observed with Biodestroyer of Straw – 29.64 million/g. Under non-inversion tillage, regardless of depth, the highest ammonifier count was achieved with Organic Balance, exceeding other variants by 1.00–4.65 million/g.

The number of nitrifying microorganisms also changed under the influence of microbial preparations and tillage methods, although differences were smaller than for ammonifiers. Changes in soil microbiological activity also affected nutrient status. For example, nitrate content in the arable layer at the beginning of sorghum growth was highest under Ecostern treatment – 64.5 mg/kg, and

11.3–13.7 mg/kg lower under Organic Balance, Bionorm, and Straw Destroyer treatments. Subsequently, the variant with Organic Balance showed a significant advantage. The nitrate content was notably lower under Cellulose Destroyer treatment. Soil nitrification capacity, although slightly influenced by microbial preparations, showed less pronounced changes. At the beginning of sorghum growth, nitrification capacity was higher – 160.3–167.7 mg/kg under Biodestroyer of Straw, Ecostern, and Cellulose Destroyer, exceeding other variants by 9.0–16.4 mg/kg.

Studies established a high correlation between the degree of wheat straw decomposition after 90 days and nitrate content (NO_3) in the 0–30 cm soil layer under grain sorghum during the first half of its growing season (r = 0.56–0.80), which decreased later in vegetation. A similar correlation existed between nitrate content and sorghum yield.

In conclusion, achieving high crop yields largely depends on adequate nutrient supply. In organic farming, one effective measure is the use of microbial preparations, which accelerate the conversion of unavailable post-harvest residues into plant-accessible forms. Such biologized approaches improve soil fertility by increasing organic matter and humus content. Field experiments demonstrated that changes in soil biological activity and nutrient status during straw decomposition under microbial treatments and different tillage methods significantly affect crop yield (Table 21).

21. Grain yield of sorghum depending on soil tillage and microbial decomposer treatments, t/ha

Destructor preparation (factor A)	Soil tillage (factor B)			Average for factor A
	plowing to a depth of 20–22 cm	non-inversion tillage		
		deep chisel tillage to a depth of 20–22 cm	shallow disc tillage to a depth of 12–14 cm	
Control	3.57	3.22	3.13	3.31
Stubble biodestructor	4.38	4.04	3.50	3.97
Ecostern	4.63	4.22	4.01	4.29
Organic-balance	5.01	4.57	4.04	4.54
Bionorm	4.21	3.90	3.52	3.88
Cellulose destructor	4.28	3.92	3.67	3.96
Average for factor B	4.35	3.98	3.65	3.99
LSD_{05}, t/ha by factors: A – 0,23; B – 0,20; AB – 0,38				

Source: author’s development.

Against the background of plowing, the highest yield was obtained with the use of the Organic-Balance preparation – 5.01 t/ha, and Ekostern – 4.63 t/ha. Straw treatment with Bionorm, Cellulose Destructor, and Stubble Biodestructor preparations resulted in a yield reduction of 21.3–26.5 %. Switching to deep non-inversion tillage caused an average decrease in sorghum grain yield of 9.3 %. With shallow non-inversion tillage, sorghum treated with

Ekostern and Organic-Balance preparations produced almost the same yield – about 4 t/ha. Dispersion analysis of the experimental data allowed determining the differences in the effect and interaction of the studied factors on sorghum yield. Microbial preparations had the greatest impact on yield formation, accounting for 61.3 %.

Soil tillage had a slightly lower effect – 32.2 %. The interaction of the studied factors and the residual value was insignificant – within 3 %.

The use of biomass from sorghum and asteraceous crops as fuel offers promising prospects for strengthening energy independence, which is particularly important under current conditions. Moreover, the combustion of biomass or its further processing (such as bioethanol and biogas production) is characterized by environmental safety. Considering the consequences of military actions and the need for post-war reconstruction, the demand for biofuels and bioenergy equipment in Ukraine has significant potential, creating favorable conditions for the active implementation of alternative energy sources.

At present, sweet (forage) sorghum is primarily cultivated for silage and green fodder. Its leafy-stem biomass serves as a valuable raw material and heat carrier within a closed alcohol production cycle. In terms of energy value, sweet sorghum is among the most attractive crops due to, firstly, its much lower water requirements (which increases the potential area of cultivation) and, secondly, the ability to produce both leafy-stem biomass (30–40 t/ha) and a considerable grain yield (2.5–3.0 t/ha), which can also be used for bioethanol production. Taking grain yield into account, ethanol output per hectare increases substantially, reaching 7,000 liters or more per year.

The cultivation of Jerusalem artichoke (*Helianthus tuberosus* L.) can serve as an effective means of addressing the issue of competition between food and bioenergy production. Unlike cereal crops, Jerusalem artichoke can be successfully grown on low-productive and marginal lands, which are increasingly considered an important reserve for expanding areas under energy crops. The production of pellets from sorghum and Jerusalem artichoke biomass helps solve a range of environmental and technological problems, promoting the development of biomass-based thermal energy production and the diversification of traditional fossil fuels. This also enables the establishment of effective mechanisms in Ukraine to stimulate the biomass energy sector.

Silphium perfoliatum is considered a “new” crop in modern global agriculture, yet it represents a promising, high-yielding, perennial forage crop belonging to the Asteraceae family. It contains a relatively high sugar content (14–20 %) and accumulates substantial biomass. Regarding biomass accumulation, it is worth noting that Silphium has a very high productive potential – yielding on average up to 100 tons or more of green mass per hectare annually for 15–25 years. After harvesting, a significant amount of post-mowing and post-harvest residues remains in the field – about 8 t/ha (compared to no more than 5 t/ha after maize), which also contributes to improving soil fertility.

The cultivation of sorghum and asteraceous bioenergy crops is becoming increasingly relevant under conditions of growing climate aridity, as these plants are characterized by high drought tolerance and the ability to produce stable biomass even under limited water availability. Their use as a source of renewable energy contributes to the diversification of agricultural production, the reduction of dependence on traditional energy resources, and the enhancement of national energy security. In the context of Ukraine's post-war recovery, the cultivation of such crops may serve as an effective tool for restoring degraded lands, creating new employment opportunities in rural areas, and ensuring the environmentally sustainable development of the agricultural sector.

The heat capacity of sorghum and asteraceous biomass, as well as the yield of conditional biofuel, depends on the species, agronomic conditions of cultivation, biomass processing methods, and its chemical composition. The calorific value of sweet sorghum biomass ranges from 17 to 19 MJ/kg (on a dry matter basis). Its high sugar content makes it suitable for bioethanol production. The biomass of grain sorghum has a slightly lower energy content (16–18 MJ/kg, depending on variety and moisture level), but it can be efficiently used for solid biofuels or biogas generation.

According to calculations, one ton of green sweet sorghum biomass can produce 45–55 liters of bioethanol, while biogas yield reaches approximately 200–300 m^3 per ton of dry matter. For grain sorghum, biogas output is somewhat lower—about 150–250 m^3/t of dry matter. In solid fuel production (pellets or briquettes), one ton of biomass provides 15–17 GJ of heat, equivalent to 0.6 tons of conventional fuel. The biomass of broomcorn sorghum (used as solid biofuel material) is roughly equivalent to 0.5 tons of conventional fuel per ton of biomass.

Silphium perfoliatum is considered a promising crop for solid biofuel production (pellets or briquettes). The calorific value of Silphium biomass ranges from 18 to 20 MJ/kg (dry matter). One ton of dry Silphium biomass can produce 250–300 m^3 of biogas, and when processed into pellets or briquettes, provides 17–19 GJ of energy, equivalent to 0.7–0.8 tons of conventional fuel.

The calorific value of the green mass and residues of Jerusalem artichoke (*Helianthus tuberosus* L.) ranges from 17 to 19 MJ/kg. Due to its high inulin content, the tubers can be used for bioethanol production–approximately 70–100 liters of bioethanol per ton of tubers. Additionally, one ton of plant residues (green mass) yields 200–250 m^3 of biogas. When processed into solid fuel (pellets or briquettes), one ton of Jerusalem artichoke biomass provides 16–18 GJ of energy, equivalent to 0.6–0.7 tons of conventional fuel.

According to the results of the conducted research, representatives of the genera *Sorghum* and *Silphium* exert a significant influence on soil microflora, which is determined by their biological activity, the morphophysiological characteristics of their root systems, and their ability to release organic substances into the soil environment. The determination of the number of microorganisms belonging to the main physiological groups, including pathogenic ones, was performed in accordance with the national standard DSTU 7847:2015 "Determination of the Number of Microorganisms in Soil by the Plate Count Method on Solid (Agarized) Nutrient Media" (2016). Specifically, the enumeration included: microorganisms utilizing mainly organic nitrogen compounds – on meat-peptone agar (MPA); microorganisms assimilating primarily mineral nitrogen compounds, including actinomycetes – on starch-ammonia agar (SAA); oligotrophs – on starvation agar (SA); pedotrophs – on soil agar (SoA); oligonitrophiles – on Ashby medium; microorganisms capable of mineralizing organic phosphorus compounds – on Menkina medium; and cellulolytic microorganisms – on Winogradsky medium. Microbial counts were expressed as the number of colony-forming units per gram of absolutely dry soil (CFU/g) with adjustment for soil moisture content. The indicators of mineralization–immobilization, oligotrophy, pedotrophy, and microbial transformation of soil organic matter (according to Mukha V.D.) were calculated from the ratios of specific microbial groups in accordance with DSTU 3750–98. The productivity indicators of the studied crops were analyzed using mathematical and statistical methods (analysis of variance, correlation, regression, and variation analysis) with the STATISTICA v.6 software package.

At the time of biomass harvesting of sorghum crops, the number of microorganisms belonging to the main physiological groups in the soil ranged from 0.1 to 39.0 million CFU/g. The soils of all samples were highly enriched with ammonifiers; the abundance of oligotrophs and pedotrophs ranged from "rich" to "very rich," while that of amylolytic microorganisms and oligonitrophiles varied from "moderate" to "rich." The soils were also enriched with microorganisms capable of mobilizing phosphorus from organic compounds and with cellulolytic microorganisms.

According to agrochemical analysis, the content of organic matter in the 0–10 cm soil layer, recalculated to humus, was elevated (3.10 %), while in the 10–20 cm and 20–30 cm layers it was of medium level. The soil solution reaction was close to neutral (pH 6.0–6.4). The content of mobile phosphorus forms in the 0–10 cm and 10–20 cm layers was elevated (106.0–134.6 mg/kg) and medium at 20–30 cm, respectively. The content of exchangeable potassium was very high (191.0–243.7 mg/kg) and high, whereas the availability of easily hydrolyzable nitrogen was very low.

It was established that the harsh weather and climatic conditions of 2024 led to a considerable decrease in the productivity of sorghum crops, manifested in the formation of relatively low biomass yields (13.2–18.7 t/ha). The application of biopreparations contributed to an increase in biomass formation even under moisture-deficient conditions, with the bioproduct Groundfix demonstrating the highest efficiency. Sorghum – particularly sweet sorghum –

proved to be a highly efficient energy resource with significant potential for the production of bioethanol, biogas, and solid fuel (pellets). The selection of specific varieties was determined both by cultivation conditions and by the intended type of final biofuel. *Silphium perfoliatum* confirmed its suitability for the production of solid biofuel and biogas due to its high biomass productivity, while Jerusalem artichoke (*Helianthus tuberosus*) proved to be a multifunctional crop suitable for bioethanol, biogas, and pellet production.

Studies on the stress resistance of bioenergy crops in model plots indicated high resilience of Jerusalem artichoke, attributed to its natural adaptation to drought and ability to maintain stable yields on low-fertility soils. The Stress Susceptibility Index (SSI) ranged from 0.68 to 0.69, a value close to the upper stability threshold, indicating consistent productivity under stress conditions. A comparable level of stress tolerance was observed in *Silphium perfoliatum* (0.68 units), which is also adapted to poor soils and demonstrates drought resistance but requires optimal conditions during the active growth phase. *Sorghum* exhibited a higher stress tolerance (SSI 0.41–0.68) than *Helianthus tuberosus* and *Silphium perfoliatum*, reflecting its superior ability to maintain productivity under adverse environmental conditions.

In conclusion, sorghum and asteraceous bioenergy crops possess considerable potential for cultivation under drought conditions and for supporting the post-war recovery of Ukraine's agricultural sector, as they combine high environmental and energy efficiency with the capacity to restore land resources and strengthen the country's energy independence. The relevance of cultivating bioenergy crops is further reinforced by the availability of unused agricultural lands, low-productivity areas, and anthropogenically degraded or contaminated soils, which can be effectively utilized for establishing dedicated bioenergy plantations.

Agroecological justification of cultivation technologies for essential oil crops. In their study, Gamayunova et al. (2024) analyzed the prospects of diversifying oilseed crop production in Ukraine, taking into account current challenges of food security, climate change, and growing demand for high-margin crops. The authors emphasize the need to incorporate new niche crops, including essential oil plants, as a strategic pathway to enhance the competitiveness of the agricultural sector and align with export market requirements [463].

The article by Manushkina and Drobitko (2025) [464] identified a number of general trends indicating the potential of using essential oil crops in phytoremediation systems for degraded lands in the Southern Steppe of Ukraine. In particular, the study found stable adaptation of narrow-leaved

[463] Gamayunova V., Khonenko L., Mykolaichuk V., Kuvshinova A. Prospects and directions of diversification of oilseed group crops. *Scientific Horizons*. 2024. Vol. 27 (10). P. 102–112. doi: 10.48077/scihor10.2024.102

[464] Manushkina T., Drobitko A. Formation of stable soil-protective agrophytocenoses of essential oil plants in the conditions of the Southern Steppe of Ukraine. *Ukrainian Black Sea Region Agrarian Science*. 2025. Vol. 29 (1). P. 9–19. doi:10.56407/bs.agrarian/1.2025.09

lavender and medicinal hyssop to the arid and climatically unstable conditions of the region, manifested in high survival rates and winter hardiness over an extended cultivation period. A gradual increase in biometric indicators and yield over three years was observed, demonstrating the ability of these crops to effectively form agro-phytocenoses with pronounced soil-protective properties. A high level of canopy coverage indicates the significant potential of these plants in stabilizing soil surfaces and reducing erosion processes. Thus, lavender and hyssop can be considered effective elements in strategies for the ecological reclamation of anthropogenically disturbed areas.

Mykhailenko et al. (2024) demonstrated that english lavender cultivated in Ukraine exhibits high antioxidant activity and a favorable chemical profile, particularly in terms of linalool and linalylacetate content-key compounds in essential oils. This confirms its potential as a competitive raw material on the international market for natural aromatic products, especially amid rising demand for eco-friendly phytochemicals in Europe and North America [465].

The cultivation of essential oil crops is highly relevant due to their significant economic, ecological, and social potential. The demand for essential oils and products derived from essential oil plants is increasing across many industries, including perfumery, cosmetics, pharmaceuticals, and the food sector.

Military actions in Ukraine have caused substantial degradation of land resources, particularly in regions affected by active combat. Soils damaged by explosions and contaminated with heavy metals, petroleum products, remnants of munitions, and other toxic substances require effective restoration measures. Cultivating essential oil crops in areas affected by war is a strategically important step for Ukraine's ecological and economic recovery. These crops combine natural phytoremediation capabilities with high economic potential, making them an attractive tool for rebuilding the country's agricultural sector.

Essential oil products occupy an important place in global trade. Producers can achieve high revenue through exports, as many types of essential oils command high prices on international markets. Essential oil crops are economically profitable as niche crops, particularly on lands where other crops may be less productive due to climate change and soil conditions. Their cultivation contributes to high profitability in agricultural production through export-oriented products, increased investment in agriculture and processing industries, reduced dependence on traditional grain exports, and diversification of agricultural output.

Ukraine possesses significant potential for the cultivation of essential oil crops due to its favorable agroclimatic conditions. However, this potential is currently constrained by a number of key challenges, including underdeveloped processing infrastructure, a lack of innovative technologies, and low logistics

[465] Lavandula angustifolia herb from Ukraine: Comparative chemical profile and in vitro antioxidant activity / O. Mykhailenko et al. *Chemistry and Biodiversity*. 2024. Vol. 21. Iss. 9, e202400640. doi: 10.1002/cbdv.202400640

efficiency. An assessment of the economic efficiency of essential oil crop production has shown that intensification of production, modernization of technological processes, and development of infrastructure could substantially enhance the productivity and competitiveness of Ukrainian producers. Analysis of global market dynamics indicates the necessity of adapting to international economic trends, shifts in demand, and the advancement of processing technologies. Ukraine requires the expansion of investment projects, improvement of raw material processing technologies, and reduction of transportation and storage costs. Evaluation of export potential has revealed that the most promising directions for Ukrainian producers to enter international markets are primarily the European and North American markets, where demand for natural essential oils continues to grow [466].

In Ukraine, there is significant potential for cultivating narrow-leaved lavender (*Lavandula angustifolia* Mill.), lavandin (*Lavandula hybrida* Rev.), medicinal hyssop (*Hyssopus officinalis* L.), peppermint (*Mentha x piperita* L.), lemon balm (*Melissa officinalis* L.), clary sage (*Salvia sclarea* L.), and other essential oil crops.

Essential oil crops are often grown under conditions that support ecosystem preservation. These crops help maintain soil fertility, increase biodiversity, and promote the development of organic farming. The growing trend toward environmentally friendly products stimulates demand for essential oils and plant raw materials. Cultivation of crops such as lavender and lavandin also supports agritourism, craft production, the creation of local brands, and the promotion of regional characteristics. Currently, lavender is gaining popularity in landscape design in both Ukraine and Europe.

The aim of this research was to study the morpho-biological characteristics and productivity of essential oil plants of the Lamiaceae family under the conditions of the Southern Steppe of Ukraine. The studies have been conducted at the Department of Crop Production, Geodesy, and Land Management since 2018 and continue to the present. The research is based at the collection nursery of Mykolaiv National Agrarian University, the Educational and Scientific Research Center of MNAU, and the department's branches in Mykolaiv region – FG "Agrolife" and FG "Chernenko S.".

The material for the research included the following species and varieties: *Lavandula angustifolia* Mill., *Lavandula hybrida* Rev., *Hyssopus officinalis* L., *Mentha x piperita* L., *Melissa officinalis* L., and *Salvia sclarea* L. High adaptive capacity was observed in the essential oil plants of the Lamiaceae family (Fig. 1). The survival rate of the plants ranged from 85.0 % to 100 %, depending on the species, variety, and quality of the planting material. The highest survival rate was recorded in *L. angustifolia* and *L. hybrida*, reaching

[466] Drobitko A., Manushkina T., Samoilenko M., Bondar A. State and prospects of essential oils production in Ukraine and the world. *Grassroots Journal of Natural Resources*. 2025. Vol. 8 (1). P. 894–918. doi: 10.33002/nr2581.6853.080138

100.0 %. For *H. officinalis*, *M. x piperita*, and *S. sclarea*, survival ranged between 90.0 % and 97.5 %. The lowest survival rate was observed in *Melissa officinalis*, at 85.0 %.

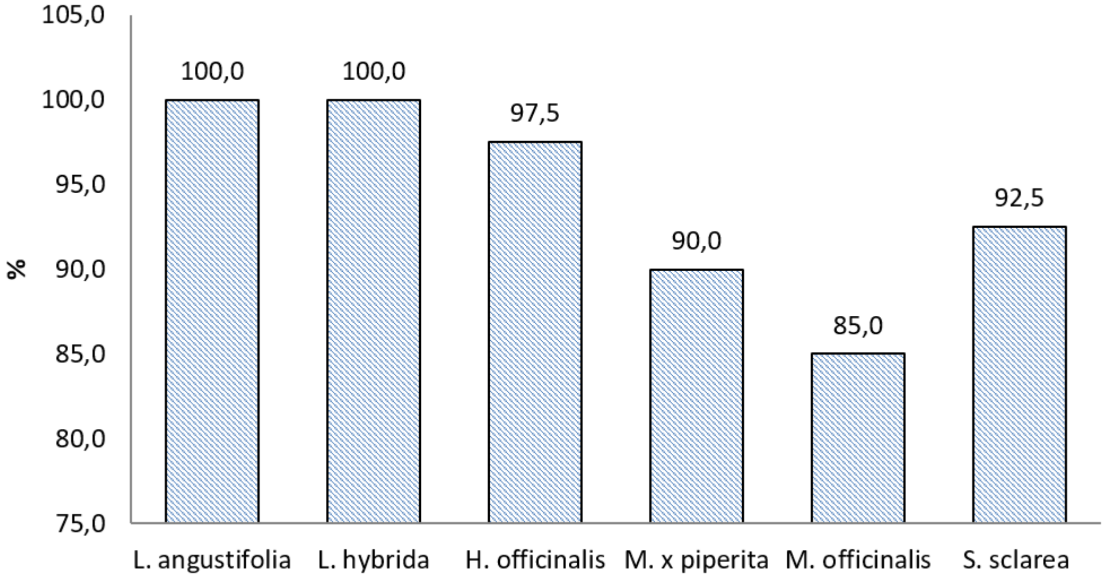

Fig. 1. Viability of essential oil plants

Source: author's development.

Winter hardiness over the three years of cultivation ranged from 80.5 % to 98.7 % (Fig. 2). During the growing seasons, plants of all studied species went through all phases of vegetation and produced biomass yields, which increased dynamically from the first to the third year and depended on the genotype and the agrometeorological conditions of the cultivation year.

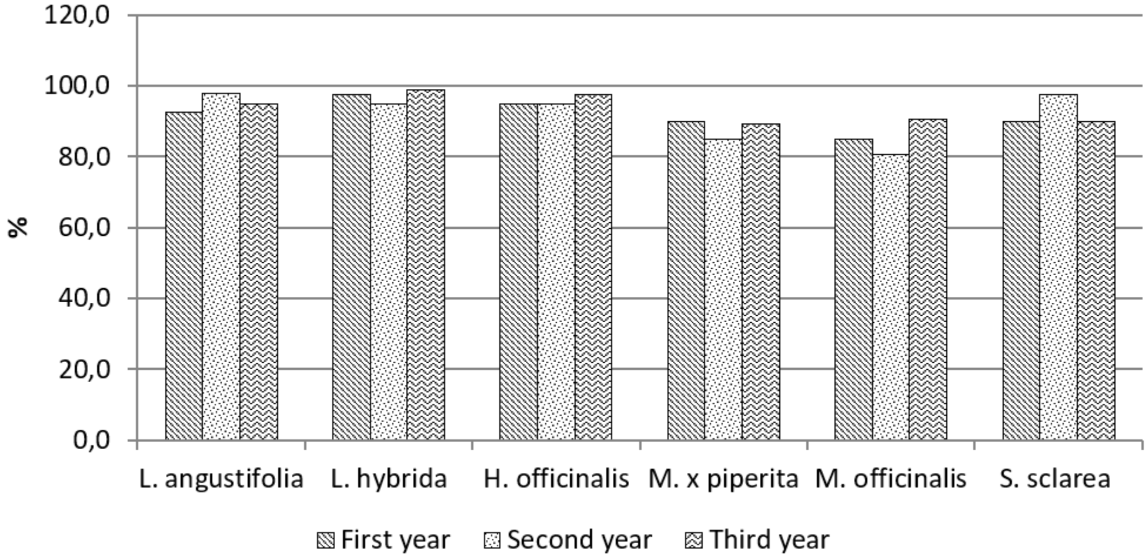

Fig. 2. Winter hardiness of essential oil plants

Source: author's development.

English lavender is a perennial evergreen semi-bushy plant that forms a spherical bush 35–60 cm high. The results of determining the biometric parameters of english lavender are shown in Table 22.

The greatest increase in shoot height was observed during the first year of vegetation, with seedling shoots reaching 15.0 cm, resulting in a growth of 16.0–23.9 cm across the studied varieties. In the second year of vegetation, bush height increased by 6.1–6.4 cm, and in the third year – by 6.0–13.6 cm. The total increase in bush height over the entire cultivation period ranged from 35.7 to 36.3 cm. Comparison between varieties indicated that during the first two years of vegetation, plants of the Imperial Gem variety exhibited greater height than those of the Hemus variety. By the third year, however, no significant differences in height were observed between the varieties, with values of 50.7–51.3 cm, consistent with their varietal characteristics.

Bush diameter measurements throughout the study were consistently higher in the Hemus variety. In this variety, bush diameter increased by 22.1 cm in the second year and 16.2 cm in the third year. In contrast, the Imperial Gem variety showed an increase of 5.4 cm and 12.3 cm in the second and third years, respectively. Overall, the bush diameter of the Hemus variety exceeded that of Imperial Gem by 6.6 cm in the first year (not statistically significant) and by 23.3 cm and 16.2 cm in the second and third years, respectively, reflecting significant varietal differences attributable to genetic traits.

22. Biometric parameters of english lavender plants, 2021–2023

Variety	Year of cultivation	Bush height, cm	Bush diameter, cm	Number of inflorescences, pcs./bush
Hemus	First	31.0 ± 2.7	51.3 ± 4.8	81.2 ± 9.1
	Second	37.1 ± 2.3	73.4 ± 6.8	334.8 ± 37.0
	Third	50.7 ± 3.7	89.6 ± 9.4	650.3 ± 20.0
Imperial Gem	First	38.9 ± 4.0	44.7 ± 5.3	53.7 ± 8.8
	Second	45.3 ± 4.7	50.1 ± 5.3	297.3 ± 32.3
	Third	51.3 ± 1.4	62.4 ± 6.8	594.9 ± 30.3

Source: author’s development.

Analysis of the dynamics of inflorescence formation in lavender revealed that during the first year of vegetation, 53.7–81.2 inflorescences per bush were formed, representing 9.0–12.5 % of the number observed in the third year. During the second year, 4.1–5.5 times more inflorescences were produced compared to the first year, accounting for 49.9–51.5 % of the third-year count. Across all years, the Hemus variety consistently exhibited a significantly higher number of inflorescences compared to Imperial Gem. The maximum number of inflorescences was recorded in the third year of cultivation. Parameters of the yield structure of narrow-leaved lavender were assessed over the three-year cultivation period (Table 23).

The parameters of the yield structure of lavender plants increased with plant age, and by the third year of cultivation, they were as follows: inflorescence length 5.5–6.8 cm, number of rings per inflorescence 5.2–6.4, and number of flowers per semi-ring 5.2–6.4. Differences between varieties in terms of yield structure were also observed. In the third year, the Imperial Gem variety produced the longest inflorescences, measuring 6.8 cm, and had the highest number of flowers per semi-ring at 6.4, while the Hemus variety exhibited the greatest number of rings per inflorescence at 6.4. Lavender inflorescences were harvested such that the length of the spikelet with the cut shoot did not exceed 18 cm. Immediately following harvest, the raw materials were weighed and their yield and moisture content determined, with the yield recalculated to standard moisture content. The results are presented in Table 24.

23. Crop structure parameters of english lavender, 2021–2023

Variety	Year of cultivation	Inflorescence length, cm	Number of rings per inflorescence, pcs.	Number of flowers per half-ring, pcs.
Hemus	First	2.9 ± 0.3	4.3 ± 0.3	3.8 ± 0.4
	Second	4.1 ± 0.2	5.1 ± 0.5	4.7 ± 0.5
	Third	5.5 ± 0.5	6.4 ± 0.8	5.2 ± 0.1
Imperial Gem	First	3.9 ± 0.4	3.5 ± 0.4	2.9 ± 0.3
	Second	5.1 ± 0.7	4.2 ± 0.2	4.0 ± 0.1
	Third	6.8 ± 0.7	5.2 ± 0.1	6.4 ± 0.8

Source: author's development.

Based on the assessment of lavender productivity during the first year of vegetation, it can be concluded that the yields of the Hemus and Imperial Gem varieties did not differ significantly and were relatively low. This trend persisted in the second year of vegetation. The highest yields were recorded in the third year, with the Hemus variety producing significantly more than Imperial Gem. In the first year, plant yields amounted to 12.7–13.4 % of the third-year yield, and in the second year – 52.0 %.

24. Yield of english lavender, 2021–2023

Variety	Year of cultivation	Yields, t/ha at standard moisture content	Increase by the first year, t/ha
Hemus	First	0.78	-
	Second	3.04	2.26
	Third	5.84	5.06
Imperial Gem	First	0.67	-
	Second	2.75	2.08
	Third	5.29	4.62
LSD_{05}	by variety factor	0.41	-
	by year of cultivation factor	1.87	-
	by the interaction of factors	2.07	-

Source: author's development.

The survival rate of medicinal hyssop plants was 90.5 % for the Natsionalnyi variety and 85.9 % for Markiz. Winter hardiness remained high throughout the study, ranging from 81.5–83.7 % in the first year to 87.1–96.4 %

in the second and third years, indicating strong adaptive capacity of the crop to adverse winter conditions.

Analysis of growth dynamics over three years of cultivation showed that the maximum plant height was reached in the third year (69.5–83.3 cm), while the minimum height occurred in the first year (30.0–41.5 cm). The number of vegetative-generative shoots per bush increased from the second year onward, averaging 54.5–67.1 in the second year and 70.4–85.9 in the third year (Table 25).

25. Biometric parameters of medicinal hyssop plants, 2021–2023

Variety	Year of cultivation	Bush height, cm	Bush diameter, cm	Number of inflorescences, pcs./bush
Natsionalnyi	First	30.0 ± 2.5	18.6 ± 1.7	37.1 ± 3.1
	Second	49.1 ± 4.3	28.9 ± 3.0	54.5 ± 5.0
	Third	69.5 ± 7.0	39.7 ± 3.7	70.4 ± 6.7
Markiz	First	41.5 ± 4.0	24.3 ± 2.3	41.5 ± 3.8
	Second	58.2 ± 5.7	33.8 ± 3.3	67.1 ± 5.3
	Third	83.3 ± 7.4	42.1 ± 6.8	85.9 ± 7.3

Source: author's development.

The study revealed that the yield of medicinal hyssop flower raw materials increased progressively from the first to the third year of cultivation (Table 26). The highest yield was recorded in the third year, ranging from 10.94 to 12.43 t/ha, with the Markiz variety producing significantly more than the Natsionalnyi variety, by 13.6 %. In the first year of vegetation, yields accounted for 21.5–28.4 % of the third-year yield, and in the second year – 61.0–66.7 %.

26. The yield of medicinal hyssop, 2021–2023

Variety	Year of cultivation	Yields, t/ha at standard moisture content	Growth by the first year, t/ha
Nationalnyi	First	2.35	-
	Second	6.68	4.33
	Third	10.94	8.59
Markiz	First	3.53	-
	Second	8.30	4.77
	Third	12.43	8.90
LSD_{05}	by variety factor	0.53	-
	by year of cultivation factor	1.93	-
	by the interaction of factors	2.24	-

Source: author's development.

Thus, under the conditions of the Southern Steppe of Ukraine, the performance and prospects of cultivating medicinal hyssop (*Hyssopus officinalis*) varieties Natsionalnyi and Markiz were assessed. Both varieties demonstrated high seedling survival and strong winter hardiness. The maximum biometric parameters of the plants were observed in the third year of cultivation.

Soil-protective properties of agrophytocenoses *L. angustifolia* Mill. and *H. officinalis* L. These crops are perennial plants capable of growing on stony, unproductive soils, and have anti-erosion properties due to their powerful root system and long life span. To determine the soil protection properties, the indicators of the projected coverage of the area by lavender and hyssop plants were determined (Table 27).

27. Projected area coverage with essential oil plants

Year of cultivation	*L. angustifolia* Mill.		*H. officinalis* L.	
	Variety Hemus	Variety Imperial Gem	Variety Nationalnyi	Variety Markiz
First	37.2	41.2	42.4	45.7
Second	47.8	52.1	63.8	69.0
Third	58.4	62.5	75.2	83.7

Source: author’s development

Based on the results obtained, it was found that the biometric parameters of plants increased progressively from the first to the third years of cultivation, which in turn enhanced the soil-protective properties of the phytocenoses. The highest projected plant cover was observed in the third year of medicinal hyssop cultivation, reaching 75.2–83.7 %. Bush density and the degree of overgrowth in disturbed areas were high, with plants growing closely together to form a dense cover. In English lavender, the projected cover in the third year was slightly lower, at 58.4–62.5 %, which can be attributed to the planting scheme. Following reclamation, the experimental plot is intended not only for the collection of plant materials but also for ecological tourism and photography, for which clearly defined rows of plants are important.

These results allow us to recommend essential oil plants of the Lamiaceae family for cultivation in the Southern Steppe of Ukraine. Prospects for further research include studying plant growth, development, productivity, and raw material quality in subsequent years of vegetation, as well as assessing their phytoremediation potential.

Achieving consistently high yields of agricultural crops requires the implementation of innovative, resource-saving, and environmentally safe technologies for the agrarian sector of the Steppe zone of Ukraine under conditions of global climate change, manifested in rising temperatures, more frequent droughts, and water deficits. In the current context, key directions in agricultural production include the greening of production processes, adaptive varietal renewal, minimization of energy expenditures, and rational use of natural resources.

Results of field experiments confirmed the necessity of an integrated approach in cereal crop cultivation technologies. For winter wheat, it was established that the highest yield (6.52 t/ha) and grain quality were achieved through timely implementation of plant protection measures combined with a seeding rate of 5 million seeds per hectare. The optimal sowing period on black fallow was determined to be from September 15 to 25. Among the studied varieties, Erythrospermum 1936 demonstrated the highest adaptability and breeding value. Regarding winter barley, the application of plant protection measures increased the average yield by 12.9 % while also enhancing protein content, with the Dostoinyi variety proving to be the most productive and genetically flexible.

The study also emphasizes the biological intensification of cultivation technologies, particularly for spring barley. It was shown that pre-sowing treatment of seeds with microbial preparations (FMB, Polymixobacterin) significantly stimulates growth processes, enhances root system development, and increases the assimilative leaf surface. As a result of inoculation, a notable yield increase of up to 1.72 t/ha was achieved, especially in the Dostoinyi variety. This approach also positively influenced the qualitative characteristics of the grain.

An important element of the adaptive strategy is crop rotation diversification through the introduction of niche crops. Field pea, as a representative of legumes, not only enhances soil fertility but also provides high yields (up to 2.68 t/ha) under an integrated protection scheme. Strategic importance is attributed to phytotechnological energy crops (sorghum, silphium, Jerusalem artichoke), as they are drought-resistant, can be grown on low-productivity soils, and have high potential for strengthening Ukraine's energy independence. For instance, sugar sorghum has the potential to produce up to 7,000 liters of bioethanol per hectare. Moreover, these crops positively influence soil microflora by enriching it with beneficial microorganisms. Among essential oil crops, medicinal hyssop and narrow-leaved lavender are promising for the Southern Steppe; besides economic benefits, they perform important soil-protective functions. For example, medicinal hyssop achieves a projected plant cover of up to 83.7% by the third year of cultivation.

Thus, the results of the study comprehensively justify the transition of Steppe agricultural production to ecologized, biologized, and resource-saving technologies as the only path toward increasing the economic competitiveness and ecological sustainability of agro-landscapes in the face of intensifying climatic challenges.