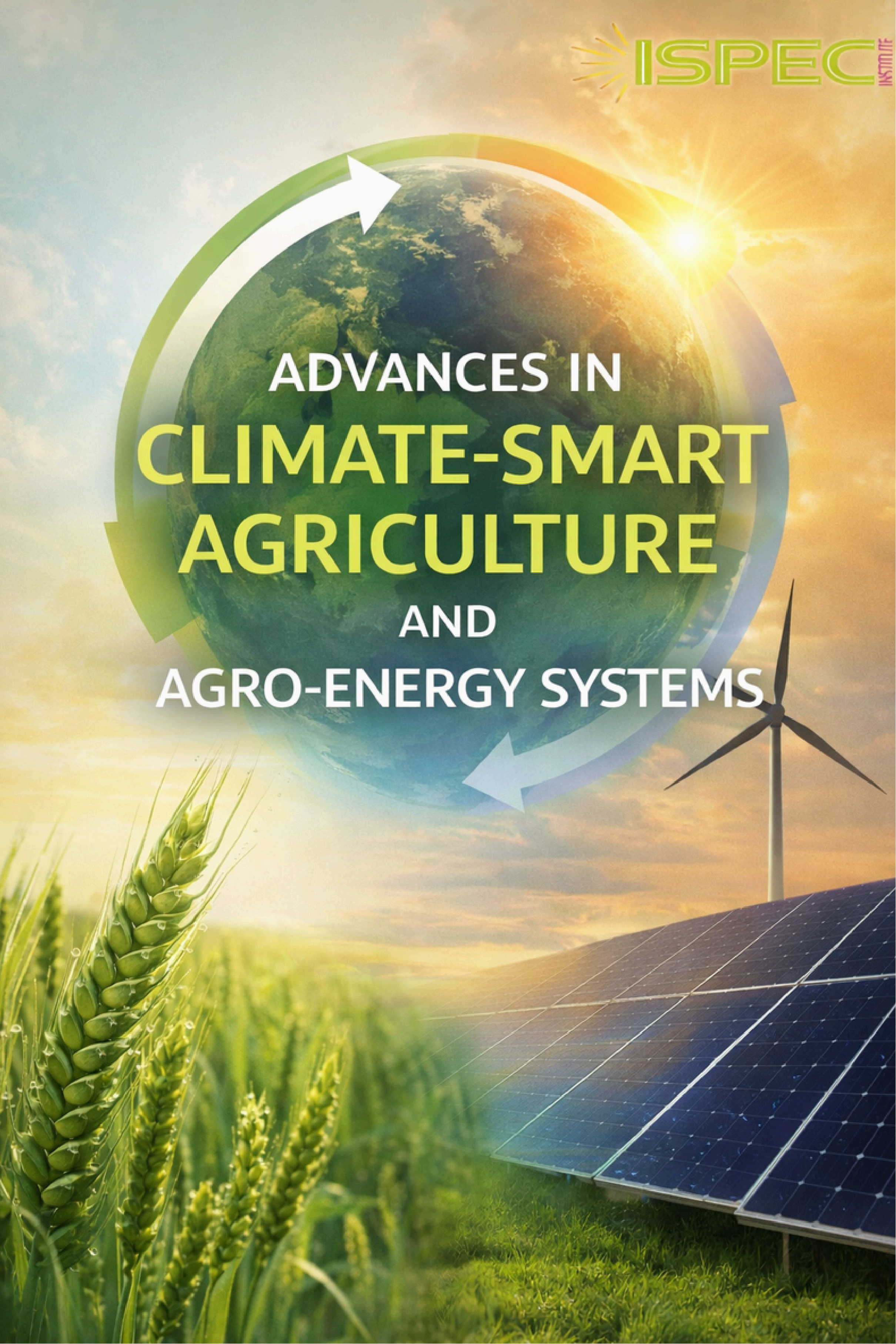
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ADVANCES IN CLIMATE-SMART AGRICULTURE AND AGRO-ENERGY SYSTEMS

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PREFACE

This volume brings together a collection of scholarly contributions that explore the critical role of agriculture in addressing global challenges related to climate change, food security, and sustainable development. As environmental pressures intensify and resource constraints become more pronounced, the need for climate-resilient and efficient agricultural systems has become increasingly urgent.

The chapters in this book address key themes such as the diversification of crop systems through niche phytoenergy crops, the implementation of climate-smart agricultural practices, and the development of sustainable livestock production strategies. These studies highlight innovative approaches to enhancing productivity while reducing environmental impacts, particularly through the efficient use of resources and the mitigation of greenhouse gas emissions.

By adopting an interdisciplinary perspective, this volume integrates insights from agricultural science, environmental studies, and sustainability research. It contributes to academic discourse while also offering practical implications for farmers, researchers, and policymakers seeking to develop resilient and sustainable food systems.

It is hoped that this book will serve as a valuable resource for scholars and practitioners interested in agriculture, climate change, and food security, while encouraging further research on sustainable and innovative solutions for the future of global food production.

Editorial Team
April 20, 2026
Türkiye

CHAPTER 1
NICHE PHYTOENERGY CROPS AS A COMPONENT OF OIL CROP DIVERSIFICATION IN UKRAINE: A COMPARATIVE ANALYSIS OF THE PRODUCTION DYNAMICS OF SAFFLOWER, MUSTARD, AND HEMP IN THE WORLD, EUROPE, AND UKRAINE

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INTRODUCTION

Under conditions of global climate change, characterized by rising average annual temperatures, increased precipitation variability, intensified droughts, and a higher frequency of extreme weather events, agricultural systems are experiencing substantial transformational pressures. These processes directly affect crop productivity, soil water regimes, and the stability of agroecosystems, particularly in risk-prone agricultural zones (IPCC, 2022; Lesk et al., 2016). The Southern Steppe of Ukraine is among the most vulnerable regions, where climate-induced stress factors already constrain agricultural productivity and increase production risks.

Additional pressure on agricultural production is exerted by contemporary economic and geopolitical factors, including market instability, supply chain disruptions, limited resource availability, and the impacts of military actions. Under such conditions, the implementation of adaptive, resource-efficient, and environmentally sustainable farming systems becomes increasingly important (FAO, 2021; KSE Institute, 2025). One of the major directions for enhancing agroecosystem resilience is the diversification of cropping systems.

Diversification of agricultural production is considered an important approach to enhancing agroecosystem resilience, as it reduces dependence on a limited range of crops, increases biodiversity, optimizes the use of natural resources, and stabilizes yields under conditions of climate variability (Altieri et al., 2015; Lin, 2011). It also plays a significant role in improving soil agrophysical and biological properties, reducing the spread of pests and diseases, and increasing the efficiency of water and nutrient use.

The issue of diversification is particularly relevant in Ukraine due to the excessive concentration of sunflowers (*Helianthus annuus* L.) in the cropping structure. In many regions, its share exceeds scientifically justified crop rotation limits, leading to soil degradation, a decline in organic matter content, deterioration of soil structure, and increased phytosanitary pressure (Chekhova, 2021; Hamaiunova et al., 2019). Under such conditions, monoculture-based systems become environmentally and economically unsustainable, especially in the context of climate change.

In this context, there is a need to revise the structure of cropping systems by introducing alternative oil crops that maintain stable productivity under water deficit and elevated temperatures. Expanding the range of such crops contributes to reducing production risks, improving the efficiency of natural resource use, and enhancing the agroecological condition of soils (Konyk & Lykhochvor, 2016; Moskva, 2016).

Diversification of oil crops is an important factor in ensuring food, environmental, and economic stability of the agricultural sector. The inclusion of alternative crops in cropping systems enhances crop rotation efficiency, improves the role of preceding crops, and contributes to the overall productivity of agroecosystems (Hamaiunova et al., 2019; Chekhova, 2021). In particular, Hamaiunova et al. (2025) demonstrated that the inclusion of alternative oil crops in crop rotations in the Southern Steppe of Ukraine improves adaptation to environmental stress, enhances soil fertility, and increases the economic efficiency of production. Similarly, global studies indicate that diversification reduces vulnerability to climate extremes and stabilizes agricultural production (Ray et al., 2015).

Recent studies further confirm that the introduction of alternative oil crops enhances agroecosystems' adaptive capacity to climate change and supports the preservation of soil fertility. Specifically, Hamaiunova et al. (2025) demonstrated that diversification of oil crops in the Southern Steppe of Ukraine improves agroecosystem resilience, optimizes cropping structures, and ensures the economic viability of production systems.

In addition to agroecological benefits, diversification has significant economic implications. Less widespread oil crops enable the formation of a broader product portfolio targeting different market segments and provide oils with valuable physicochemical properties (Wen et al., 2023). Some of these crops can also serve as feedstock for bioenergy and industrial processing, further increasing their strategic importance (Zelt, 2017).

Among promising crops, particular attention is drawn to safflower (*Carthamus tinctorius* L.), mustard (*Brassica* spp.), and hemp (*Cannabis sativa* L.), which are characterized by high drought tolerance, adaptability to diverse growing conditions, and the ability to maintain stable yields even under unfavorable hydrothermal conditions (Amaducci et al., 2015).

These crops have a wide range of applications, from food and feed production to industrial, pharmaceutical, textile, and bioenergy uses.

Industrial hemp occupies a special position among niche crops due to its high biomass productivity, significant cellulose content, and versatility of use. It serves as an important raw material for the textile, paper, construction, and composite industries, and is also considered a promising source of bioenergy feedstock. In addition, hemp can be used as a source of cellulose for the production of advanced materials, further strengthening its role in enhancing national resource independence (Amaducci et al., 2015; Small, 2015).

Therefore, diversifying oil crops is an important pathway for developing resilient, economically efficient, and environmentally sustainable agricultural systems. It facilitates the adaptation of agricultural production to climate change, improves resource-use efficiency, preserves soil fertility, and ensures the long-term stability of the agricultural sector.

1. OBJECTIVE OF THE STUDY AND ITS SCIENTIFIC RATIONALE

The aim of this study was to identify patterns in the changes of harvested area, gross production, and yield of safflower, mustard, and hemp in the world, Europe, and Ukraine over the period 2010–2024, as well as to assess the role of these crops in the diversification of crop production in Ukraine under conditions of climate change, economic instability, and structural transformation of the agricultural sector. This approach allows not only the evaluation of the extent of crop distribution but also the assessment of their potential as components of more resilient farming systems aimed at reducing production dependence on a narrow range of traditional crops. In contemporary scientific literature, crop diversification is recognized as one of the most effective strategies for enhancing the resilience of agricultural systems to climate variability, economic fluctuations, and environmental degradation of agro-landscapes. In particular, it has been emphasized that expanding the range of cultivated crops reduces production vulnerability to external factors and increases the adaptive capacity of farming systems (Lin, 2011; Feliciano, 2019).

2. DATA SOURCES AND ANALYTICAL METHODS

The study used statistical data from the international FAOSTAT database for the period 2010–2024. The analysis included indicators such as harvested area, gross production, and yield, enabling comprehensive characterization of the scale of cultivation, productivity, and development dynamics of the studied crops at the global, European, and national levels. Data processing was carried out using comparative analysis, time series analysis, and generalization methods. This approach is appropriate for identifying long-term trends, as changes in harvested area and gross production sensitively reflect the agricultural sector's response to climatic, economic, and regulatory shifts.

3. RESULTS AND DISCUSSION OF CROP DIVERSIFICATION TRENDS

To assess current development trends in niche crops and determine their role in diversifying crop production, a comparative analysis of the dynamics of harvested area for safflower, mustard, and hemp worldwide, in Europe, and in Ukraine over the period 2010–2024 was conducted (Table 1). The analysis of this indicator is particularly informative, as harvested area is the most responsive to changes in economic viability, demand for processed products, agro-climatic conditions, and regulatory policies. In addition, its dynamics allow for assessing the actual level of integration of alternative crops into cropping systems and identifying directions for further expansion of production.

In a broader context, such an assessment is consistent with contemporary approaches that consider diversification as a key factor in enhancing the adaptability of agricultural systems to environmental changes (Lin, 2011; Feliciano, 2019).

The analysis of the dynamics of harvested area of niche crops reveals significant differences in the rates and patterns of their development, confirming the heterogeneity of distribution conditions even among drought-tolerant and technologically promising crops. At the global level, safflower shows considerable variability in cultivated area, ranging from 649.5 to 1205.0 thousand hectares, with pronounced peaks in 2016 and 2022.

Table 1 Dynamics of harvested area of safflower, hemp, and mustard in the world, Europe, and Ukraine, thousand hectares (2010–2024), thousand ha

	Safflower			Hemp			Mustard		
	Europe	World	Ukraine	Europe	World	Ukraine	Europe	World	Ukraine
2010	4.32	834.84	0.30	2.55	5.28	1.22	246.54	790.59	106.40
2011	13.51	804.10	0.22	2.85	5.57	1.19	211.62	701.08	46.90
2012	16.35	968.59	0.20	3.55	6.42	1.16	179.51	614.46	49.32
2013	74.81	896.90	0.20	3.75	6.35	1.14	212.51	657.71	54.07
2014	119.78	893.05	0.20	3.97	6.48	1.16	305.86	814.39	96.30
2015	243.83	1053.75	0.21	3.23	5.91	1,16	239.26	679.93	58,80
2016	435.82	1169.71	0.20	4.35	6.84	1.15	219.05	727,61	44.50
2017	155.71	861.52	0.21	5.62	8.15	1.16	217.57	670,15	39.50
2018	55.17	655.20	0.21	5.85	8,49	1.16	322.88	884.75	52.40
2019	107,17	649,53	0.21	7.15	42.24	1.16	344.22	851.88	48.30
2020	175.19	784.68	0.21	8,02	31.00	1,16	196,40	630.04	23.20
2021	242.53	859.84	0.21	8.86	37.32	1.16	203.43	644.20	20.40
2022	277.74	1204.97	0.21	8.68	43.62	1.16	248.74	847.12	18.50
2023	325.82	1041.00	0.21	7.10	34.98	1.16	336.42	980.11	85.00
2024	238.74	835.60	0.21	7.51	28.49	1.16	264.49	876.99	38.20

Such variability may indicate a high sensitivity of the crop to changes in market conditions and to water availability in the main production regions. This is consistent with scientific findings, which consider safflower a crop with high tolerance to water deficit and salinity stress; however, its productive performance largely depends on specific growing conditions and agronomic management (Hussain et al., 2016). In Europe, the dynamics of safflower area are even more contrasting: a sharp increase to 435.8 thousand hectares in 2016 was followed by a decline and subsequent recovery in 2021–2023. In Ukraine, safflower cultivation areas remain consistently low, indicating the underutilization of its adaptive potential under increasing aridization.

Mustard demonstrates a more active, but also unstable, developmental pattern. Globally, its cultivated area ranges from 614.5 to 980.1 thousand hectares, with an overall expansion trend observed in 2022–2023, whereas in Europe, the dynamics follow a wave-like pattern. In Ukraine, mustard cultivation is characterized by particularly high variability in cultivated area, which may be attributed to the combined influence of domestic market conditions, export orientation, and the production's sensitivity to weather fluctuations. These trends are consistent with research findings indicating that, under climate change conditions, white mustard may gain new opportunities for expansion in Europe as an alternative oil crop, while more traditional crops, such as rapeseed, may lose part of their suitable growing areas (Jaime et al., 2018). This supports considering mustard as a crop that can enhance the flexibility of cropping systems under increasing climatic uncertainty.

In contrast to safflower and mustard, hemp exhibits a more structured developmental trajectory, particularly in Europe. In Europe, a gradual increase in cultivated area, followed by stabilization, has been observed, indicating a more systematic market formation for this crop and an expansion of its industrial applications. At the global level, changes in cultivated area are less uniform, likely associated with shifts in regulatory frameworks and fluctuations in demand for fiber, seeds, biocomposites, and other processed products. In Ukraine, hemp cultivation is concentrated in relatively stable areas, suggesting not market saturation but rather significant potential for further expansion. This interpretation is consistent with recent review studies, which consider industrial hemp a multifunctional crop with high suitability for various applications, including cultivation on marginal lands, as well as considerable potential for adaptive agricultural production and industrial processing (Blandinières et al., 2022; Dudziec et al., 2024).

Overall, the results indicate that the development of safflower, mustard, and hemp follows clearly differentiated patterns determined by a combination of agro-climatic, economic, and regulatory factors. At the same time, the sustained interest in these crops at both global and European levels confirms their importance as potential components of a renewed cropping structure.

For Ukraine, this is particularly significant given the need to reduce dependence on excessive sunflower concentration in crop rotations, enhance the ecological stability of agroecosystems, and promote a more balanced use of agricultural resource potential. Therefore, safflower, mustard, and hemp should be considered not only as niche crops but also as promising elements of crop production diversification capable of increasing the adaptability of the agricultural sector to climatic and market changes (Lin, 2011; Feliciano, 2019; Jaime et al., 2018; Dudziec et al., 2024).

Safflower (*Carthamus tinctorius* L.) is a valuable oilseed crop characterized by a high level of ecological plasticity and adaptability to arid growing conditions. Its ability to maintain stable productivity under water deficit, high temperatures, and low soil fertility contributes to its distribution in arid and semi-arid regions worldwide. Owing to its well-developed taproot system, safflower efficiently utilizes deep soil moisture reserves, which represents a key mechanism of its drought tolerance (Emongor, 2010; Singh & Nimbkar, 2006). In addition, the crop is capable of adapting to stress conditions through morphological and physiological adjustments, resulting in improved water-use efficiency (Kaya et al., 2007).

Beyond its agroecological advantages, safflower has considerable economic importance. Its seeds contain high-quality oil rich in polyunsaturated fatty acids, which is widely used in the food, pharmaceutical, and industrial sectors (Weiss, 2000). Despite these benefits, safflower cultivation in Ukraine remains limited, underscoring the crop's underutilized potential as an important component of agricultural diversification.

Mustard is one of the most dynamic and promising niche oilseed crops. It is characterized by a short growing season, high adaptability to diverse soil and climatic conditions, and a wide range of applications, from food production to bioenergy (Rakow & Raney, 2003). Mustard is particularly valuable as a green manure crop, as its incorporation improves soil organic matter content, enhances soil structure and water-holding capacity, and stimulates soil microbial activity (Kirkegaard et al., 1993). Moreover, due to its biofumigation properties, it can reduce the incidence of soil-borne pathogens and pests (Matthiessen & Kirkegaard, 2006).

The inclusion of mustard in crop rotations increases yields of subsequent crops and improves soil nutrient status (Kirkegaard et al., 2008). However, significant fluctuations in its cultivated area are largely driven by market conditions, export orientation, and demand instability, which increases production risks.

In today's climate change context, safflower and mustard can be considered important components of oilseed diversification, contributing to increased resilience of agroecosystems and to the economic efficiency of production (Ray et al., 2015).

Hemp is a multifunctional technical crop with broad prospects for use across various industries and is of strategic importance to Ukraine. Due to its high cellulose and strong fiber content, it is considered a valuable raw material for the textile, paper, construction, bioenergy, and composite industries (Amaducci et al., 2015; Dudziec et al., 2024; Blandinières et al., 2022). At the same time, in the context of war, the search for domestic sources of strategic raw materials necessary to sustain national production and strengthen the state's resource independence becomes particularly relevant for Ukraine (FAO, 2022).

In this context, hemp is of practical interest as a potential source of cellulose-containing raw materials for specialized applications in certain high-tech areas (Zakrevska, 2024; Salentijn et al., 2015). Cartridges with hemp-based gunpowder are characterized by a lower mass, which significantly reduces the total weight of the ammunition (Coffeeshop.ua, n.d.; Ukrinform, 2022; Johnson, 2018). This is important for the military, who are in full gear for a long time. In addition, such ammunition is characterized by improved ballistic properties: increased bullet speed (up to 800 m/s), higher flight range, and firing efficiency (ZN.UA, 2022, Smith, 2019).

Hemp cellulose burns more intensely than cotton, leaving minimal residue, and is less sensitive to moisture, which provides better storage conditions (Kostic et al., 2008). Historically, the development of materials based on plant cellulose has contributed to the improvement of many technical products (Rowell et al., 2000). For a long time, the main source of suitable cellulose components was cotton, but the search for alternative plant raw materials has led to increased attention to hemp (Small & Marcus, 2002).

Hemp raw materials are considered a promising alternative to traditional cellulose sources due to their physicochemical properties, high fiber content, and good technological characteristics (Amaducci et al., 2015).

This is especially important for Ukraine, which seeks to build its own raw material base and reduce dependence on imported resources (FAO, 2022). Hemp as a source of cellulose has a number of advantages, including high productivity, significant biomass yield and wide processing capabilities (Karus & Vogt, 2004). Hemp cellulose is characterized by valuable technological properties, which determines its interest in the production of special materials (Faruk et al., 2012). The high fiber content, which can reach up to 80%, determines its prospects for various industrial applications (Kostic et al., 2008).

In addition, hemp is widely used in other industries. Its fiber is used in the production of fabrics, paper, ropes, building materials, biocomposites and other innovative products (Salentijn et al., 2015). Hemp fibers are characterized by high strength, durability and resistance to mechanical loads, which makes them promising for modern industrial production, in particular in areas where a combination of lightness, strength and environmental friendliness of the material is required (Faruk et al., 2012).

Cultivation of industrial hemp is economically feasible, since the crop is characterized by relative unpretentiousness to growing conditions, resistance to certain adverse factors and high biomass yield per unit area (Amaducci et al., 2015). This increases its importance as a raw material base for various sectors of the economy and creates the prerequisites for expanding its scope of application. Thus, hemp has significant strategic development potential, which is due to its multifunctionality, wide possibilities of industrial processing and growing demand for products on the domestic and world markets (Salentijn et al., 2015).

In modern Ukraine, this crop is important not only from an agrarian and economic perspective, but also for building national raw material security, developing its own production of special materials, and strengthening the state's resilience in the face of military challenges (FAO, 2022). At the same time, the stability of hemp cultivation areas in Ukraine indicates the presence of organizational and regulatory restrictions, which confirms the need to improve state policy to support the industry (FAO, 2022).

Overall, niche crops are an important factor in diversifying crop production in Ukraine. Under conditions of climate change, increasing aridization, and rising risks associated with conventional farming systems, their cultivation may help enhance the resilience of agricultural production, improve the efficiency of resource use, and expand the export potential of the agricultural sector.

To assess the productivity of niche crops and determine their adaptive potential under different soil and climatic conditions, a comparative analysis of the yield dynamics of safflower, hemp, and mustard worldwide, in Europe, and in Ukraine over the period 2010–2024 was conducted.

Yield is one of the most important indicators of crop production efficiency, as it integrates the effects of environmental conditions, agronomic practices, and the level of production intensification.

The analysis of this indicator enables not only evaluating the extent to which the biological potential of crops is realized but also identifying patterns of change over time and the sensitivity of crops to climate variability and management-related factors. Such analysis becomes especially relevant in the current global climate change, characterized by rising temperatures, water scarcity, and increasing risks to agricultural production.

The data presented in the table reflect interregional differences in the yields of niche crops and allow identification of general patterns in their formation, as well as prospects for their use as an element of crop diversification.

The analysis of the yield dynamics of niche crops (safflower, hemp, and mustard) worldwide, in Europe, and in Ukraine over the period 2010–2024 indicates varying levels of stability and adaptability among the studied crops.

It was found that safflower seed yield worldwide is characterized by relatively stable values ranging from 0.73 to 0.93 t/ha, with only minor fluctuations depending on the year of cultivation (Fig. 1). In Europe, variability is more pronounced, ranging from 0.46 to 0.80 t/ha, which may be associated with instability of climatic conditions and the structure of cultivated areas. In Ukraine, safflower seed yield remains stable at 0.50–0.52 t/ha, confirming the crop's high adaptability, though it also indicates an under-realized productive potential.

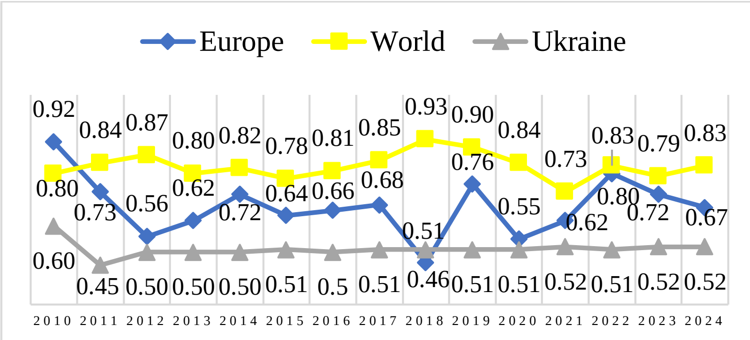

Fig. 1. Dynamics of safflower seed yield, t/ha

Hemp is characterized by moderate yield variability in Europe (0.27–0.49 t/ha) and considerably greater variability worldwide (0.43–1.11 t/ha), where peak values were recorded in 2019–2020 (Fig. 2). In Ukraine, the crop shows relatively stable yields (0.50–0.55 t/ha), which indicates its adaptation to local soil and climatic conditions, but also points to the limited adoption of intensive cultivation technologies.

Mustard has the highest productivity among the studied crops. Globally, its seed yield ranges from 0.74 to 1.09 t/ha, with an upward trend observed in 2020–2022 (Fig. 3). In Europe, yield ranges from 0.49 to 0.82 t/ha, while in Ukraine it ranges from 0.56 to 0.98 t/ha. In certain years (2021 and 2023), peak values were recorded, indicating the considerable productive potential of this crop under favorable conditions.

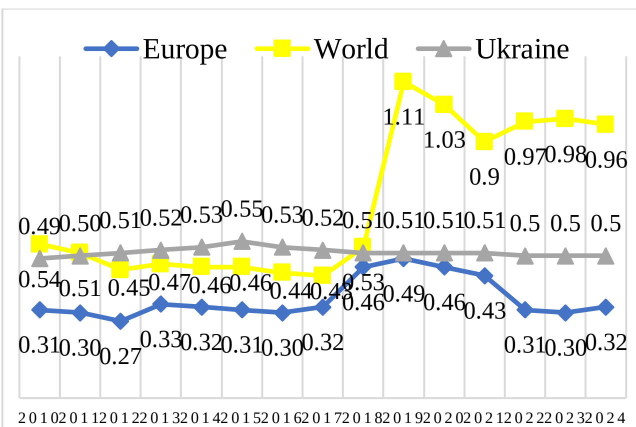

Fig. 2. Dynamics of hemp seed yield, t/ha

The results indicate that yields of niche crops are less variable than their cultivated areas, confirming their high ecological plasticity. Safflower is characterized by stable productivity even under fluctuations in cultivated area, which makes it suitable for arid conditions. Hemp shows relatively uniform yield indicators in Ukraine, whereas at the global level, its productivity depends heavily on the level of technological development. Mustard is the most productive crop among those studied; however, its yield is more sensitive to weather conditions and agronomic factors.

In general, it has been established that niche crops can maintain a relatively stable yield even under conditions of climate change, thereby enhancing their role in crop production diversification. Particularly promising is the expansion of cultivation in Ukraine, where a combination of relatively stable productivity and insufficient realization of the potential of these crops is observed.

The analysis of gross safflower production indicates significant variability of this indicator both globally and in Europe (Table 2). Worldwide, production volumes fluctuated between 587.2 and 1002.6 thousand tons, with the highest value recorded in 2022, reflecting market instability and the crop's dependence on market conditions. In Europe, variability was even more pronounced: from 4.0 thousand tons in 2010 to 288.4 thousand tons in 2016, followed by a decline with subsequent partial recovery. In Ukraine, gross safflower production remained consistently low–at the level of 0.10–0.11 thousand tons–confirming the limited spread of the crop and the insufficient utilization of its potential.

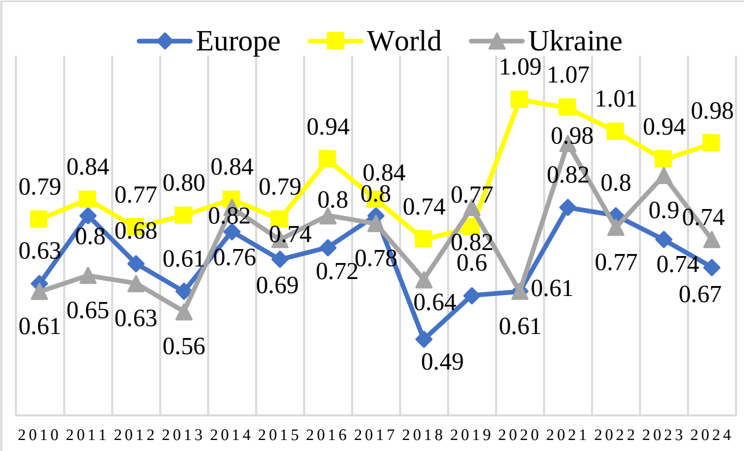

Fig. 3. Dynamics of mustard seed yield, t/ha

Hemp production exhibited a more moderate trend in Europe and pronounced fluctuations globally. In Europe, production volumes gradually increased from 0.79 to 3.83 thousand tons in 2021, followed by a slight decline. Globally, total production ranged from 2.72 to 46.74 thousand tons, with a sharp increase in 2019, likely driven by changes in demand and the expansion of hemp product applications. In Ukraine, this indicator remained almost unchanged at 0.57–0.63 thousand tons, indicating stability but limited crop development dynamics.

Table 2 Dynamics of gross production of niche crops (safflower, hemp, and mustard) in the world, Europe, and Ukraine (2010–2024), thousand tons

Рік	Safflower			Hemp			Mustard		
	Europe	World	Ukraine	Europe	World	Ukraine	Europe	World	Ukraine
2010	3.99	664.72	0.18	0.79	2.84	0.60	155.21	623.52	64.40
2011	9.80	678.28	0.10	0.85	2.84	0.60	169.06	588.98	30.30
2012	9.11	844.43	0.10	0.97	2.89	0.60	121.50	474.09	30.98
2013	46.07	721.63	0.10	1.23	3.00	0.59	130.68	525.27	30.17
2014	85.78	730.65	0.10	1.25	2.95	0.62	232.57	682.76	79.44
2015	157.17	825.33	0.11	1.02	2.72	0.63	164.00	536.13	43.55
2016	288.43	947.78	0.10	1.31	3.01	0.61	157.04	686.50	35.58
2017	106.03	735.56	0.10	1.79	3.52	0.60	174.98	564.18	31.00

2018	25.37	609.02	0.11	2.71	4.46	0.59	159.36	658.60	33.34
2019	81,30	587.20	0.11	3.48	46.74	0.59	206.94	656.35	39.53
2020	96.75	656.16	0.11	3.72	32.02	0.59	119.56	685.27	14.04
2021	151.50	627.47	0.11	3.83	33.43	0.59	167.03	687.15	19.92
2022	222.73	1002.61	0.11	2.67	42.30	0.58	200.15	852.23	14.17
2023	234.38	819.67	0.11	2.11	34.10	0.58	248.71	923.96	76.91
2024	159.72	692.52	0.11	2.37	27.41	0.57	177.70	862.02	28.42

Mustard showed the greatest variability in gross production. Globally, its production ranged from 474.1 to 924.0 thousand tons, with peak values recorded in 2023–2024, indicating growing demand for this crop. In Europe, significant variability was also observed, ranging from 119.6 to 248.7 thousand tons. In Ukraine, mustard production showed particularly sharp fluctuations: from 14.0–14.2 thousand tons in 2020–2022 to 79.4 thousand tons in 2014 and 76.9 thousand tons in 2023. Such dynamics indicate a high dependence of the crop on economic conditions, profitability levels, and market trends.

The obtained results indicate that the gross production of niche crops is determined not only by their biological characteristics but also by market, technological, and institutional factors. Safflower has a high adaptive potential; however, its production in Ukraine remains at a minimal level, underscoring its underestimation within the cropping system. Hemp demonstrates stability in Ukraine and gradual growth in Europe, confirming its potential, particularly through the development of processing and the expansion of its application areas. Mustard proved to be the most dynamic crop, capable of rapidly responding to changes in demand, making it an important yet riskier element of diversification. Overall, the analysis of gross production confirms that niche crops exhibit different levels of realization of their production potential in Ukraine. This highlights the need for a more flexible approach to crop structure formation, focused on combining adaptive, economically attractive, and strategically perspective crops.

The scientific novelty of the study lies in conducting a comprehensive comparative analysis of the dynamics of cultivation of niche crops–safflower, mustard, and hemp–at the global, European, and Ukrainian levels over the period 2010–2024.

Regional features of the formation of cultivated areas, yields, and gross production were identified, and the role of these crops as an important element in adapting agricultural production to climate change and diversifying crop production was substantiated.

The practical significance of the obtained results lies in their potential to optimize the structure of sown areas, increase the resilience of agricultural production, and reduce production risks. The findings can be used to develop strategies for niche crop production, build diversified agroecosystems, and design state support programs for the agricultural sector.

CONCLUSIONS

A comprehensive analysis of cultivated areas, yields, and gross production of safflower, hemp, and mustard at the global, European, and Ukrainian levels has shown that the studied crops differ significantly in both their distribution scale and the patterns of realization of their productive potential. It was established that gross production is determined by the interaction of two main components–sown area and yield level–while their ratio and degree of influence vary across crops, regions, and production conditions.

For safflower, the main factor driving variability in gross production is changes in cultivated area, whereas yield remains relatively stable over time. This indicates the crop's high ecological plasticity and its ability to maintain stable productivity even under unfavorable conditions. At the same time, the limited distribution of safflower in Ukraine indicates its underutilized potential as a drought-tolerant alternative crop suitable for conditions of climate aridization.

Mustard shows significant variability in both cultivated areas and yields, resulting in the most dynamic pattern of gross production among the studied crops. This indicates a high sensitivity of mustard to changes in market conditions, weather factors, and the level of technological support. At the same time, in favorable years, the crop demonstrates high productivity, confirming its considerable potential as a component of crop production intensification and diversification.

Hemp, unlike other crops, is characterized by more stable cultivated areas in Ukraine and moderate yield variability, which ensures relatively stable production levels. Such dynamics indicate a high degree of adaptation of the crop to local soil and climatic conditions. At the same time, significant fluctuations are observed globally, driven by regulatory frameworks, market demand, and the expansion of industrial applications for hemp products.

The generalization of the study results showed that the yield of niche crops, in most cases, shows lower variability than that of their cultivated areas. This confirms their relatively high ecological plasticity and their ability to maintain stable productivity under changing environmental conditions. At the same time, cultivated areas act as the main regulator of production volumes, as they respond more rapidly to economic incentives, changes in demand, and agricultural policy.

At the regional level, it was found that Ukraine has significant potential to expand production of niche crops, due to favorable soil and climatic conditions, the availability of scientific support, and the need to optimize the structure of sown areas. However, the limited distribution of the studied crops indicates the presence of constraining factors, among which economic, technological, and regulatory-organizational components play a key role.

Overall, the results indicate that safflower, mustard, and hemp exhibit distinct developmental patterns; however, all can be considered important reserves for diversifying crop production in Ukraine. Their wider introduction may enhance agroecosystem resilience, reduce production risks, optimize resource use, and contribute to a more balanced structure of agricultural production.

In the future, expanding areas under niche crops should be considered a priority for adapting the agricultural sector to climate change, enhancing product competitiveness, and ensuring the long-term stability of crop production. Further research should focus on improving cultivation technologies, increasing the realization of crop genetic potential, and providing economic justification for their introduction across Ukraine's diverse soil and climatic zones.

Summary generalization

- Niche crops offer greater yield stability than traditional crops under conditions of climate variability, making them an effective means of enhancing the adaptability of agroecosystems in risk-prone farming areas.
- The main limiting factor in the development of niche crops in Ukraine is not their biological potential, but rather the institutional and economic conditions for their implementation, which necessitate improving support policies and providing technological assistance for production.

Practical recommendations

1. **Optimization of cropping patterns**
   It is advisable to gradually increase the share of safflower, mustard, and hemp in crop rotations, especially in the conditions of the Southern Steppe of Ukraine, in order to reduce soil pressure and minimize risks associated with excessive sunflower monoculture.
2. **Development of adaptive cultivation technologies**
   It is necessary to implement resource-saving, biologically oriented technologies to enhance crop productivity under conditions of moisture deficit and elevated temperatures.
3. **Breeding and seed supply**
   Expanding the use of adapted varieties and hybrids that are drought- and temperature-stress-resistant is essential to improve yield stability.
4. **Development of market and processing infrastructure**
   Increasing the economic attractiveness of niche crops requires establishing stable marketing channels, developing domestic processing, and promoting the export of value-added products.
5. **Improvement of state policy**
   It is necessary to improve the regulatory framework, particularly regarding the cultivation of industrial hemp, and to support producers through state incentives and innovation-driven development tools.

6. **Scientific and advisory support**

   It is recommended to strengthen the role of research institutions in promoting niche crops by developing regionally adapted technologies, conducting demonstration trials, and providing advisory services to producers.

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