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**AGROECOLOGICAL ASPECTS OF
ORGANIC SOYBEAN PRODUCTION
IN EU COUNTRIES**

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This article examines a range of agroecological factors influencing the efficiency of organic soybean cultivation within the European Union. The significance of the topic stems from the EU's strategic focus on achieving protein self-sufficiency and meeting the objectives of the "Farm to Fork" strategy, which aims to expand organic farmland to 25% by 2030. At the same time, increasing climate instability presents new obstacles for pesticide-free agricultural practices. The study aims to provide a systematic analysis of the current state of the EU organic soybean sector, identify key abiotic risks, and propose adaptation strategies to enhance crop yields.

The research methodology combines statistical analysis of data from Eurostat and FiBL, a comparative review of regional practices in France, Austria, Romania, and Germany, as well as a content analysis of recent field experiments conducted by European research institutions. Findings reveal that while organic soybean acreage has grown significantly-by 158% over five years-yields remain inconsistent due to hydrothermal stress. The most critical challenges identified include flower abortion under temperatures above 32°C and reduced nitrogen fixation caused by insufficient moisture levels. The study highlights that effective adaptation in the EU relies on three key strategies: selecting ultra-early soybean varieties (maturity groups 000/00), using heat-resistant inoculants, and adopting water-saving techniques such as cover crops and living mulch. The novelty of this research lies in its comprehensive analysis of the conflict between organic farming standards and climatic constraints. The practical importance of these findings lies in the potential application of European adaptive farming models in Ukraine to strengthen its role as a major exporter of organic protein. Specific recommendations include localizing soybean breeding efforts and introducing precision mechanical methods for weed control to further enhance productivity.

Keywords: *organic soybean, agroecology, European Union, climate change, protein sovereignty, adaptive breeding, nitrogen fixation, drought tolerance.*

Table 3., Ref. 10.

Problem Statement. The increasing demand for plant-based protein across EU countries, coupled with the "Farm to Fork" strategic initiative, calls for a significant expansion of organically farmed soybean areas. However, efforts to intensify production while adhering to environmental standards are met with various agroecological challenges. These include achieving high yields without the use of synthetic fertilizers and pesticides, addressing soil degradation linked to monoculture practices, and managing the complexities of weed control. Striking a balance between economic viability and maintaining the biodiversity of agroecosystems remains a pressing issue for Europe's agricultural sector [1].

Literature Review. The European Protein Strategy sets ambitious targets, yet the EU's self-sufficiency in plant proteins, particularly soybeans, remains alarmingly low at just 5–8%. Annually, member states import around 30–34 million tonnes of soybeans and soybean meal, predominantly sourced from Brazil and Argentina. The situation is even more challenging for organic soybeans.



Despite a 158% increase in EU organic soybean acreage, now covering 155,000 hectares, domestic production still lags behind growing demand. As a result, a significant proportion of organic raw materials must be imported, with 57% coming from China and additional amounts from India. This dependency not only poses logistical challenges but also undermines the principle of fostering localized production and shorter supply chains [2]. The transition to organic production is occurring against a backdrop of escalating climatic instability. The primary obstacles include moisture deficits, temperature stresses, and technological complexities. Soybean is extremely sensitive to drought, particularly during the flowering and pod-filling stages. Extreme droughts in Europe (specifically in 2022 and 2025) led to significant yield losses in major production regions, such as France, Austria, and Romania. Heatwaves exceeding +30 °C cause flower abortion, which becomes a critical factor in organic farming where rapid stress compensation with chemical stimulants is impossible. In organic systems, weed and pest control without synthetic pesticides requires perfect adherence to crop rotations and mechanical cultivation, which further desiccates the upper soil layer under drought conditions [3].

Modern European agricultural science is transitioning from traditional intensification methods to emphasizing adaptive breeding and fostering ecosystem resilience. Researchers from organizations like FiBL (Research Institute of Organic Agriculture) and Agroscope are placing significant attention on selecting crop varieties suited for organic farming under the challenges posed by climate change [4].

Research by Zimmer et al. (2021) demonstrates that for organic farms in Central Europe, the key lies in utilizing varieties from the 000 and 00 maturity groups. This allows plants to use spring moisture more efficiently and avoid peak August droughts [5]. Works by Reckling et al. (2022) emphasize that in organic systems, priority is given not to potential maximum yield but to variety stability (plasticity). Scientists focus on varieties with powerful root systems capable of absorbing moisture from deep soil horizons, which is critical in herbicide-free technologies [6].

A distinct line of research (e.g., Westermeier et al., 2023) is dedicated to the ability of varieties to form an effective symbiosis with *Bradyrhizobium japonicum* bacteria at high temperatures. It has been established that drought suppresses nodule bacteria earlier than the plant itself; therefore, breeding varieties that maintain nitrogen-fixing capacity at +35 °C is a priority for the EU [7].

The LegumeHub and Euro-Leaks projects: within these pan-European initiatives, the role of crop rotation diversification is being studied. It has been proven that organic soybean demonstrates a 15–20% higher resistance to climatic stresses when grown after cover crops, which preserve soil structure and moisture [8].

Although substantial advancements have been made in breeding, the impact of genotype-by-environment (G×E) interaction under organic nutrient management has not been thoroughly explored. The majority of soybean varieties available in the EU market have been developed for conventional farming systems, and their adaptability to low-input conditions with restricted weed control demands further investigation [9, 10].

Thus, the agroecological aspect of organic soybean production in the EU lies in resolving the dilemma: how to ensure protein autonomy under increasing climatic risks while maintaining strict environmental standards and farm profitability.

Research Objectives. Drawing upon the analysis of the experiences of EU countries, the objective is to develop a theoretical framework and systematically organize the agroecological principles for organic soybean cultivation. This involves evaluating how climatic factors influence crop productivity within organic farming systems and pinpointing key areas for adapting technologies-through breeding innovations and agronomic practices-to address the plant protein deficit currently affecting the European market.

Materials and Methods. The study's methodological framework is grounded in a systematic approach to agroecosystem analysis, incorporating the principles of environmental determinism. To fulfill the research objectives, a combination of general scientific and specialized methods was employed. The statistical-economic method facilitated the examination of trends in cultivated areas, gross harvests, and organic soybean import volumes within EU countries. Data sources included official records from Eurostat, FiBL (The World of Organic Agriculture), and analytical reports by the European Commission. Using the comparative-geographical method, regional agroclimatic conditions for soybean cultivation across Southern, Central, and Eastern Europe were analyzed to pinpoint areas with heightened climatic risk. Additionally, systematic monitoring and content analysis were applied to review scientific literature and field experiment findings from European research initiatives, particularly the Legumes Translated and ReMIX projects. These studies focused on assessing the efficiency of symbiotic nitrogen fixation and evaluating drought tolerance in soybean varieties. Agroecological synthesis is utilized to consolidate technological practices such as crop rotation, the use of cover crops, and mechanical weed control, highlighting their role in maintaining soil fertility and biodiversity. The abstract-logical generalization method is applied to derive conclusions and provide recommendations for adapting European experiences in organic soybean production.

The foundation of the study relies on EU legal and regulatory frameworks, particularly Regulation (EU) 2018/848 concerning organic production. It also incorporates research conducted by prominent ecologists and agronomists, alongside climate change data monitored through the Copernicus programme.

Results. The current stage of development of the European agricultural sector is characterized by a steady trend towards the expansion of soybean cultivated areas, driven by the EU's protein independence strategy and the growth of the organic food segment. During the 2017–2022 period, the area under organic soybean in the EU increased by 158% (from 60,000 ha to 155,000 ha). Organic bean production almost doubled during this timeframe, reaching approximately 280,000 tonnes in 2022, despite a significant decline in yields caused by that year's summer droughts.

More than 90% of the total organic soybean volume in the EU is concentrated in five countries. As of 2022–2023, the leaders are: France and Austria (collectively accounting for 52% of production); Romania (19%); Germany (11%); Italy (10%).

Notably, in 2023, significant growth rates were also demonstrated by Slovakia (+48.7%) and Poland (+39%). Approximately 75% of the organic soybean produced in the EU is used in animal husbandry (primarily for meal production), while the food sector accounts for about 15%.

Domestic production satisfies only a small portion of the overall demand. Each year, the EU imports around 35 million tonnes of soybeans, predominantly GMO varieties for the conventional sector. Within the organic segment, the primary external suppliers are China, accounting for 57% of imports, and India at 33%. Additionally, Ukraine continues to bolster its standing, securing a place among the top three largest exporters of organic products to the EU as of 2024.

Despite record rates of area expansion, organic soybean production in the EU remains vulnerable to weather anomalies, leading to yield volatility (for instance, a 3.4% drop in total EU soybean output in 2024 due to summer heat, despite a 10% increase in sown areas).

Organic soybean production in the EU demonstrates high sensitivity to climatic anomalies, due to limited possibilities for rapid stress mitigation using synthetic inputs. The primary determinants of yield are the temperature regime and moisture availability.

Soybean is highly susceptible to drought, particularly during its flowering and pod-filling stages (R2–R6). Research indicates that the combined effects of heat stress and moisture deficit can lead to a 30–40% decline in organic soybean yields. For example, the severe drought in 2022 caused a notable reduction in yields across key regions such as France and Austria, even though the overall sown areas had been increased. Temperature increases above +30 °C during the reproductive phase cause flower abortion and underdeveloped pods. In organic farming, where anti-stress chemical stimulants are not used, plants are forced to rely solely on their own genetic plasticity.

In Northern and Central Europe (Germany, Poland), low temperatures at the beginning of the growing season are a limiting factor, delaying root system growth and reducing the efficiency of symbiosis with nitrogen-fixing bacteria.

Climate change is driving a shift in the geographic centers of agricultural productivity. Projections suggest that by 2050, the optimal regions for soybean cultivation will move from the South to areas in Northern and Eastern Europe. In Southern Europe, including parts of Italy and Romania, growing organic soybeans without irrigation is becoming more challenging. This is attributed to an anticipated 21.5% drop in yields by the end of the century under less favorable climate scenarios.

In organic systems, the lack of moisture combined with intensive mechanical cultivation (for weed control) leads to accelerated mineralization of organic matter and additional soil desiccation. This necessitates the implementation of water-saving technologies, such as mulching or the use of cover crops.

Data analysis from recent years confirms that despite the increase in sown areas, the gross harvest of organic soybean shows significant volatility due to extreme weather events (the droughts of 2022 and 2024) (Table 1).

Table 1

Dynamics of organic soybean area and yield in key EU countries (2022–2024)

Country	Area, thsd ha (2024)	Area change compared to 2022, %	Average yield, t/ha	Climate impact (2022-2024)
France	48.5	+12%	1.8 – 2.4	Yield drop of 20% due to heat in the Rhone Valley
Austria	32.1	+15%	2.1 – 2.8	Stability due to advanced irrigation systems
Romania	28.4	+22%	1.2 – 1.9	Critical drop (-35%) in 2024 due to drought in the south
Italy	18.2	-5%	2.5 – 3.1	Area reduction due to water deficit for irrigation
Germany	16.5	+18%	1.9 – 2.5	Constraints due to a cold spring and excessive rainfall in the north

Source: Data based on preliminary Eurostat reports and FiBL branch assessments [4].

The data in Table 1 indicate a "scissors effect" between acreage and productivity: for instance, in Romania and France, even a substantial expansion of soybean cultivation areas could not compensate for drought-induced losses, resulting in a stagnation of the gross harvest.

Table 2 emphasizes that the temperature regime plays a more crucial role in the organic sector, as the restricted availability of biological products limits the ability to effectively restore crops following thermal shock.

Table 2

Sensitivity of organic soybean to abiotic stresses by ontogenesis phases

Development phase	Climatic factor	Impact on yield	Risk level for organic production
Seedling / Emergence (VE-V1)	Temperature < +10 °C	Inoculation delay, uneven emergence	High (weeds outcompete soybean)
Flowering (R1-R2)	Temperature > +32 °C	Flower abortion (pod drop)	Critical
Pod filling (R5-R6)	Moisture deficit	Small-seededness, reduced protein content	High
Maturation (R7-R8)	Excessive rainfall	Pod shattering, fungal diseases	Medium

Source: developed by the author based on [4].

Agro-climatic instability remains the key challenge hindering the EU's progress toward protein self-sufficiency. This highlights the critical importance of developing adaptive breeding strategies and adopting comprehensive moisture management systems within the organic sector. To address the adverse effects of climate change and boost organic soybean production in the EU, researchers and agricultural unions are prioritizing the development and implementation of advanced adaptation strategies. The primary solutions include adaptive breeding and genetic plasticity, biotechnological solutions such as inoculation and symbiosis, and innovative agrotechnical practices. The main emphasis is shifting away from pursuing maximum yield potential toward choosing varieties with high ecological adaptability.

In Central and Northern Europe, particularly in Germany and Poland, ultra-early varieties belonging to maturity groups 000 and 0000 are prioritized. These varieties enable plants to complete their grain-filling phase before the peak temperatures of August hit, thereby reducing the risk of early autumn frosts. Breeding emphasizes developing varieties with greater lower pod clearance to reduce losses during mechanical harvesting and promoting rapid early growth. This enables soybean plants to shade inter-rows more effectively, helping to suppress weeds naturally without relying on herbicides.

In organic farming, nitrogen fixation serves as the primary source of nitrogen nutrition. This requires the use of inoculants derived from *Bradyrhizobium japonicum* strains that can operate effectively at soil temperatures of +8 to +10 °C, a vital aspect for early sowing periods. Additionally, the creation of biological products capable of sustaining their activity during brief heatwaves is essential to ensure consistent plant nutrition during key growth phases.

Technology adaptation is aimed at preserving moisture and biodiversity. This includes growing soybean after rye or mustard (the "roller-crimper" technology). Mulch from crop residues protects the soil from overheating and moisture evaporation, while also acting as a natural barrier against weeds (Table 3).

Table 3

Comparative efficiency of adaptation measures in EU countries

Technological solution	Impact on yield	Main advantage for organic production	Implementing countries
Early sowing (000 varieties)	+15–20%	Avoiding summer drought	Germany, Austria
Mulching (No-till)	+10–12%	Soil moisture conservation	France, Italy
Dual inoculation	+25–30%	Maximum nitrogen fixation	Romania, Poland

Source: developed by the author based on [4].

Intercropping: experiments in growing soybean alongside maize or small-grain cereals. This improves resource utilization (light, water) and reduces the risk of massive pest outbreaks, which is critical for organic systems operating without insecticides. Furthermore, the use of precision farming systems for mechanical inter-row cultivation via GPS-guided robotics minimizes damage to the soybean root system.

Conclusions and Prospects for Further Research. The study of agroecological factors influencing organic soybean production in EU countries highlights several important findings. Although the area dedicated to organic soybean cultivation has grown remarkably, surpassing 150% in recent years, the European market still heavily relies on imports. A major obstacle to achieving protein self-sufficiency lies in the significant yield fluctuations driven by abiotic stresses such as droughts and extreme temperatures. Enhancing the resilience of organic farming systems in the EU depends largely on transitioning to adaptive breeding strategies (e.g., maturity groups 000/00) and employing biotechnological innovations like cold- and heat-tolerant inoculants. These approaches help maximize the crop's genetic potential without relying on synthetic fertilizers.

The most successful outcomes are observed on farms that combine organic production with moisture-conserving techniques such as mulching and cover cropping, alongside precision mechanical weed control, which collectively reduce the risk of soil degradation during dry spells. Considering Ukraine's path toward European integration and its climatic parallels, the country should prioritize the following actions: expedite the certification process for Ukrainian organic soybeans in alignment with Regulation (EU) 2018/848 to enhance entry into Europe's premium markets; collaborate with European institutes such as FiBL to establish joint demonstration fields for testing ultra-early soybean varieties suited to the conditions of the Northern Steppe and Polissya regions; and encourage domestic production of highly efficient inoculants capable of supporting nitrogen fixation under critical temperature conditions. Future research opportunities include an in-depth analysis of the economic feasibility of intercropping soybeans with other crops within Ukraine's organic crop rotation systems.

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АНОТАЦІЯ

АГРОЕКОЛОГІЧНІ АСПЕКТИ ОРГАНІЧНОГО ВИРОБНИЦТВА СОЇ В КРАЇНАХ ЄС

У статті досліджено комплекс агроекологічних чинників, що визначають ефективність вирощування органічної сої в умовах Європейського Союзу. Актуальність теми зумовлена стратегічним курсом ЄС на білкову незалежність та цілями програми «Від ферми до виделки» (Farm to Fork), що передбачають збільшення частки органічних земель до 25% до 2030 року. Водночас зростаюча кліматична нестабільність створює нові виклики для безпестицидних технологій. Метою роботи є системний аналіз сучасного стану органічного соєвого сектору ЄС, виявлення критичних абіотичних ризиків та обґрунтування адаптаційних стратегій для підвищення врожайності культури. Методологія дослідження базується на статистичному аналізі даних Eurostat та FiBL, порівняльному підході до вивчення регіонального досвіду Франції, Австрії, Румунії та Німеччини, а також контент-аналізі останніх польових експериментів європейських інститутів. У ході дослідження встановлено, що попри динамічне зростання площ (на 158% за 5 років), валові збори сої залишаються волатильними через гідротермічні стреси. Визначено, що найбільш критичним фактором для органічних систем є абортивність квіток при температурах понад +32 °C та пригнічення азотфіксації внаслідок дефіциту вологи. Результати аналізу свідчать, що успішна адаптація в ЄС базується на трьох стовпах: селекції ультраскороспілих сортів (групи 000), використанні терморезистентних інокулянтів та впровадженні вологозберігаючих технологій, таких як покривні культури та жива мульча. Наукова новизна полягає у систематизації агроекологічних суперечностей між вимогами органічного стандарту та кліматичними обмеженнями. Практична значущість роботи полягає у можливості імплементації європейських моделей адаптивного землеробства в Україні для зміцнення її позицій як провідного експортера органічного протеїну. Сформульовано рекомендації щодо локалізації селекції та впровадження методів точного механічного контролю бур'янів.

Ключові слова: органічна соя, агроекологія, Європейський Союз, кліматичні зміни, білкова незалежність, адаптивна селекція, азотфіксація, посухостійкість.

Табл. 3., Літ. 10.

Інформація про автора

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