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MAIZE BREEDING FOR ENHANCED ADAPTABILITY TO CLIMATE CHANGE IN EUROPE

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Based on a structured statistical assessment of the implementation outcomes of European Union maize breeding programs, particularly regarding their efforts to enhance the adaptive potential of modern maize genotypes, a set of generalizations and conclusions on the effectiveness of these programs has been formulated.

The network of national institutions and genetic-breeding centers across Europe has been analyzed and characterized. These institutions focus on targeted maize breeding using local landraces or base populations, applying mono- or multi-trait selection for resistance to key stress factors that significantly limit the yield potential of Europe's high-intensity maize hybrids.

The content of breeding programs from leading European seed companies –such as KWS, Limagrain, Syngenta, Corteva Agriscience, MAS Seeds, and Euralis (Lidea brand) – has been summarized and reviewed. These programs were specifically assessed regarding the incorporation of current and projected climate change impacts across Europe, with attention to scaling these strategies to other regions. Key traits emphasized included drought and cold tolerance, heat and osmotic stress resistance, and comprehensive tolerance to the most damaging diseases and pests.

Over a 45-year evaluation period, the incremental improvements in resistance traits of developed maize hybrids were systematized, focusing on their responses to climatic variability during the growing season, soil fertility requirements, lodging resistance, and resistance to phytophagous pests and phytopathogens. This analysis considered the close relationship between the intensity of stress factors affecting plant growth and development, the realization of bioproductivity, and the dynamics of regional climatic regimes (temperature, water availability, etc.). As a final outcome, the most successful European-bred genotypes in terms of climatic adaptability and abiotic stress resistance were identified. These genotypes have gained recognition both in Europe and globally and are also suitable for cultivation in Ukraine.

Keywords*: breeding, hybrids, adaptive resistance, climate change, breeding programs, abiotic and biotic stress factors.*

Table 2., Fig. 3., Lit. 35.

Problem Statement. Monitoring of hydrothermal resources across Europe within the trend assessment interval of 1991–2020 in comparison with 2021–2023, an increase daily temperature by 1.0738 °C, a decrease relative humidity by 0.9414%, and decrease precipitation by 130 mm were recorded [1].

Such patterns indicate persistent processes of climate aridization, a decline in favorable moisture supply regimes, and clear signs of warming. Under these conditions, considering the stable relationship between the identified changes and negative yield trends of agricultural crops ranging from 3.8% to 15% [2], stable prerequisites are being formed both for revising technological time regulations in crop cultivation systems typical for regional production and for reducing the overall adaptive potential of existing varietal and hybrid compositions [3].

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In this context, the use of genotypes not adapted to the observed climatic changes increases yield losses within a 3–5-year identification cycle up to 20–30% when zonal cultivation technologies are applied in southern Europe and 10–20% in northern regions. Such loss levels were already recorded during 2000–2010 [4, 5], with projections of significant increases under continued growth of average daily temperatures, uneven seasonal temperature amplitudes, reduced relative humidity, and prolonged periods of atmospheric and soil moisture deficit. Modern statistical models developed up to 2050 predict a high probability of changes in the spectrum of cultivated crops, which may affect the preservation of traditional food structures and raw materials for processing. This requires the immediate development of adaptive and flexible crop production technologies based on climate-resilient varieties and hybrids as a fundamental element [6].

For maize, which ranks among the three most cultivated crops in Europe and constitutes a significant sector of agricultural production, and which is highly sensitive to climate change – particularly in terms of soil and atmospheric moisture availability [7] – the breeding of climate-resilient varieties and hybrids is one of the key strategic objectives for ensuring economically viable and regionally flexible production in Europe and globally [8].

Based on the above generalizations, maize breeding aimed at developing and implementing models of varieties and hybrids with high adaptive potential and climate resilience for European Union countries represents a priority issue. Its resolution will enable the establishment of flexible maize grain production systems with a stable dependence on the available hydrothermal potential of agricultural territories.

Analysis of Recent Research and Publications. Maize breeding in Europe has undergone a multi-stage evolution of program objectives, forming a structured system of breeding directions [9–11]. Most researchers identify several key components necessary for the future development of European maize breeding practice.

First, the development of drought- and heat-tolerant hybrids resistant to atmospheric and soil moisture deficits is considered essential, enabling the preservation of maize yield potential and minimizing productivity decline in arid farming zones [12, 13], particularly under pronounced moisture deficits in Southern and Central Europe [14]. Second, breeding efforts focus on developing combined-type maize genotypes that integrate early maturity with high yield (bioproductivity) across biomass, grain, and seed productivity levels. This approach significantly reduces risks of heat and water stress by shortening the growing period and enabling successful completion of critical phenological stages before peak summer temperatures [15–17].

Third, breeding aims at creating low-input hybrids through the development of highly productive plant morphotypes with well-developed root systems, optimized leaf surface area with high photosynthetically active radiation use efficiency, and reduced transpiration water consumption.

At the same time, these hybrids should demonstrate high nutrient uptake efficiency from soil and applied fertilizers, enabling the reconfiguration of fertilization strategies and economic components of maize production [18–20].

Fourth, there is a need to breed hybrids with complex adaptive resistance to diseases and pests, based on plant architecture characterized by pronounced anti-phytophagous and anti-pathogenic traits, as well as developmental asynchrony between maize plants and associated pests and pathogens, including quarantine species in certain cultivation zones [21]. This approach allows minimization of risks associated with climate-driven changes in pest populations and pathogen spread, particularly in Southern Europe [6], and may reduce yield losses due to these factors by at least 15% [17]. Fifth, breeding programs aim to develop maize plants with desirable biochemical characteristics, both in terms of leaf-stem biomass for bioenergy use (e.g., biogas production) [11, 15, 18] and grain quality for food, feed, bioenergy, and other technological applications [22]. This direction is increasingly important in the context of ongoing diversification of grain markets in Europe and worldwide, evolving logistics and trade networks, and the growing importance of exporting processed maize products with higher added value [10, 19].

It should be emphasized that these five breeding directions represent conceptually important components of European maize breeding programs aimed at achieving maximum yield levels while ensuring genetic flexibility and plasticity under unstable hydrothermal resource conditions, including both deficit and excess scenarios [11, 23].

At the same time, achieving these program objectives is impossible without accelerated breeding cycles incorporating process-based crop growth models and genomic selection [8, 24]. These approaches significantly improve the identification and integration of “hidden” physiological traits into future genomes, such as photosynthetic efficiency under stress conditions and the ability to maintain high yields under reduced agrochemical inputs [10, 25].

Successful breeding will also be facilitated by applying advances in molecular-genomic selection, including the use of genetic resources such as endemic maize races and local landraces to introduce new stress-resistance alleles, ensure complex adaptive traits and plasticity, and design ideotypes “ideal” plants for future climatic conditions. Such ideotypes may involve modified architecture for improved radiation use efficiency, reduced water consumption, enhanced soil nutrient uptake, and integrated resistance to pests, diseases, and weeds [5, 22, 26].

However, the existence of national maize breeding programs, endemic soil-climatic features across European countries, and disparate breeding objectives – including commercial and adaptive priorities – creates challenges in identifying a unified European breeding practice and evaluating achieved goals. This necessitates a clearer synthesis of maize breeding results in Europe in light of recent climatic trends and underscores the relevance of the findings presented in this article.

Research Conditions and Methodology. The research included scientific and statistical analysis of analytical reports of the European Union concerning maize production volumes [31–33], and prospective objectives of national breeding programs focused on the development of maize breeding material for various purposes [34].

The indicated analysis include units of variation statistics [35], a general procedure of statistical comparison with the assessment of incremental indicators, and graphical interpretation over a comparable period of the last 20 years. For this purpose, programe Excel, JMP Pro 18.0.1, and Statistica 10 were used.

Presentation of the Main Research Findings. Since 2019, the system of corn breeding concentrated in the members of the ECPGR European Evaluation Network (EVA) [15, 34]) covering the main gradation nature resources. This has enabled targeted breeding for adaptability and plasticity, taking into account zonal features for aim of achieving maximum heterosis effects in hybrid recombinations of varying complexity, including saturating and backcross crosses. This breeding platform had 24 centers from 13 European countries, hosting 13 genetic banks of initial maize breeding material. Reported [9, 21, 34] that European maize landraces are highly diverse, locally adapted, and distinct populations, often yielding about half of modern hybrids but providing crucial genetic variability for climate change adaptation. These traditional varieties, introduced in the 15th century, are conserved in genebanks and actively used in breeding programs to improve stress tolerance.

Studies of European collections reveal nine centres with short geographic distances. A large proportion of genetic variance exists between individuals, with significant differentiation depending on latitude [34]. A recent large-scale study evaluating 626 maize landraces conserved in European genebanks demonstrated high genetic and phenotypic variability [15].

It has also been reported that these landraces form Western and Eastern European clusters, reflecting different routes of introduction and local adaptation. Some clusters correspond to flint and dent ancestral groups – for example, flint types adapted to northern climates and dent groups associated with warmer regions [24].

The maize landrace material to create hybrid combinations of varying structural complexity adapted in breeding practice for period 2000–2025 had different methods.

One of these approaches is the traditional breeding method, which involves various crossing schemes through recombination of selected initial landraces (including backcrossing strategies) [8]. The second approach is based on the application of molecular-genetic techniques with elements of predictive breeding and the implementation of expected adaptive and adaptively productive characteristics of the developed maize hybrids, relying on previously identified typological genotype–environment interaction responses [11].

During the period 1980–2025, the implementation of adaptive maize breeding programs in the European Union, aimed at enhancing the adaptive potential of selective varietal and hybrid maize material in terms of relative genetic gain, has confirmed its effectiveness in achieving the main target components of these programs (Fig. 1).

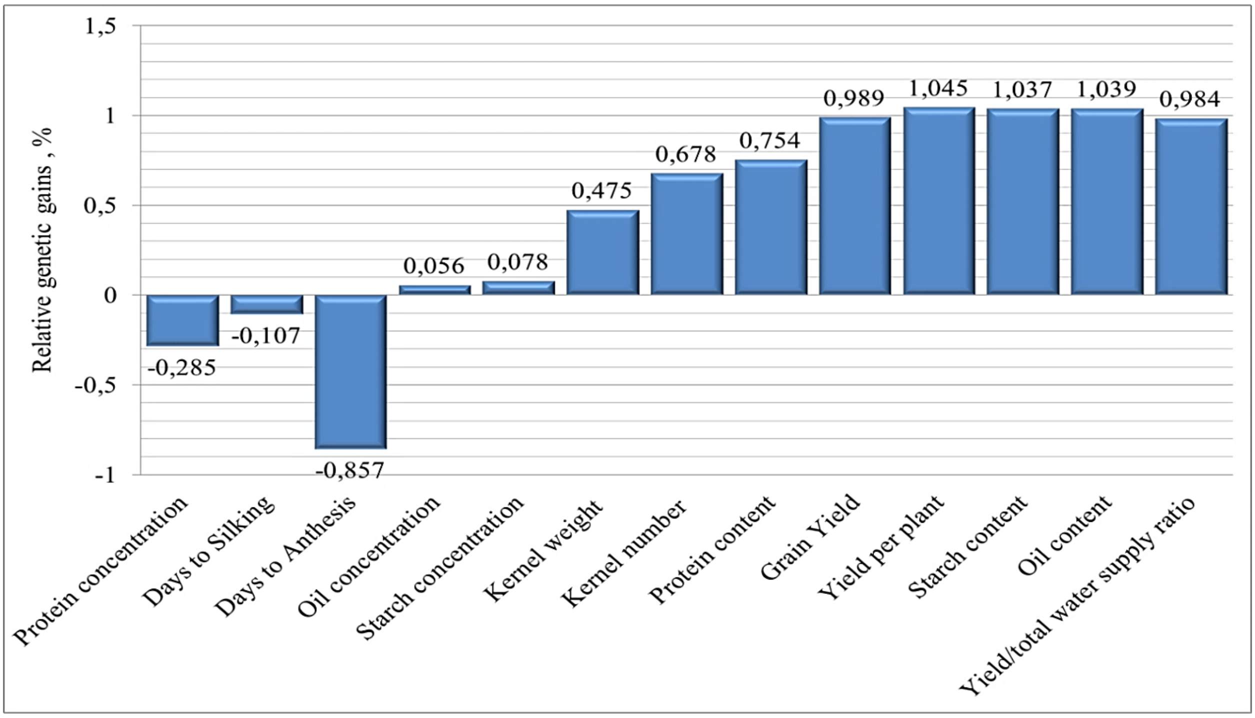

Fig. 1. Relative genetic gains for different plant trait corn hybrids in the European Union, 1980 vs 2025, %

In detailing the presented data, based on the analysis of other studies [11, 13, 21–24] from the perspective of adaptive breeding, the following program objectives were achieved in Europe during the period from 1980 to 2025:

– grain yield of selected maize hybrids increased by 32%, from 11.63 t/ha to 15.52 t/ha;

– the kernel number increased from 3,881 to 4,682 kernels m^{-2} (genetic gain of 24 kernels m^{-2} per year);

– the kernel weight increased from 254 to 286 mg/kernel (genetic gain of 0.92 mg/kernel per year);

– grain protein concentration decreased by 0.0273% per year, although total protein yield increased by 7.9 kg protein/ha per year;

– significant improvement in grain technological quality: starch content increased by 0.924% per year, oil content by 0.918% per year, and protein content by 0.641% per year;

– a decrease in days to silking (−0.93% per year) and in days to anthesis (−0.058% per year), resulting in a negative anthesis–silking interval in new hybrids;

– the yield asymptote (a proxy for yield potential) increased from 14.5 t/ha in 1985 hybrids to 18.5 t/ha in 2015 hybrids;

– the yield-to-total water supply ratio increased from 35.8 to 49.2 kg/ha/mm (a 32.3% increase).

According to the general systems of selective evaluation of newly developed maize hybrids in European practice, a comprehensive set of plant architectural parameters is applied, covering maize growth from the initial vegetative stages to physiological maturity and harvest (Fig. 2).

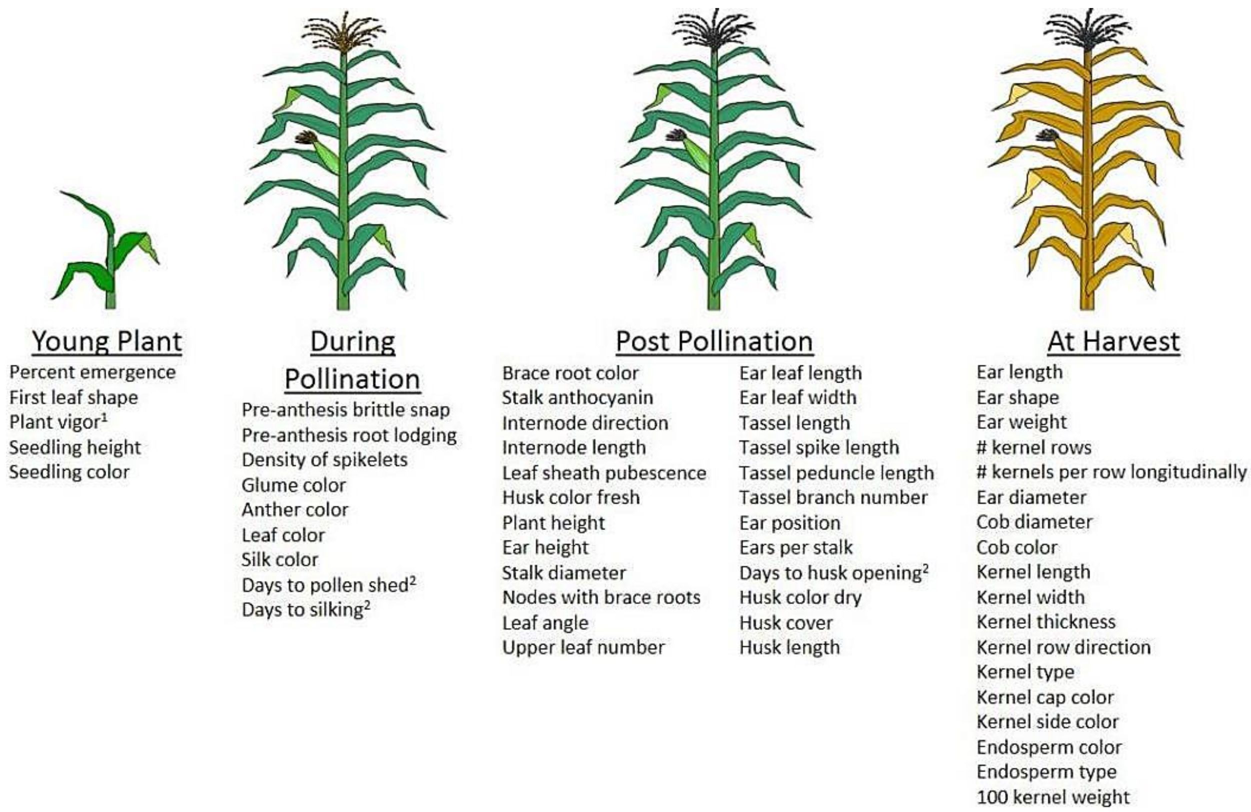

Fig. 2. The main selective morphofunctional traits of corn plants in corn breeding ([18]: [1]*evaluation on a 9-point scale;* [2]*duration of the period to reach the 50% level of transition to the corresponding phenological stage*)

Plant traits (color of plant parts cob core and kernel, serve as identifiers of heredity and indicators for monitoring the level of genetic recombination, while others reflect morphological development and the realization of yield potential. For example, cob characteristics (its length, number of kernel rows, etc.) are traditionally considered indicators of maize plant responses to environmental stress levels.

Through the combined monitoring of the dynamics of such traits (which demonstrate high dependency in maize and have been fully identified in global hybrid breeding practice [6, 15]) alongside long-term weather parameter control, it becomes possible to effectively identify hybrids adapted to both single and combined induced and non-induced stresses during the growing season. In European practice, this approach also applies to the evaluation of hybrid resistance to pests and diseases [21].

A positive outcome in maize breeding has also been the increased effectiveness in improving key adaptive traits (Fig. 3). The overall increase in adaptive potential of maize hybrids achieved through European breeding practice amounted to an incremental coefficient of 1.208 for abiotic resistance traits and 1.291 for biotic resistance traits. The main breeders and producers of maize hybrids in Europe are multinational companies and major European brands such as Limagrain (France), Syngenta (Switzerland), Corteva Agriscience (Pioneer/Dow/DuPont), KWS (Germany), MAS Seeds (France), and Euralis Semences (France).

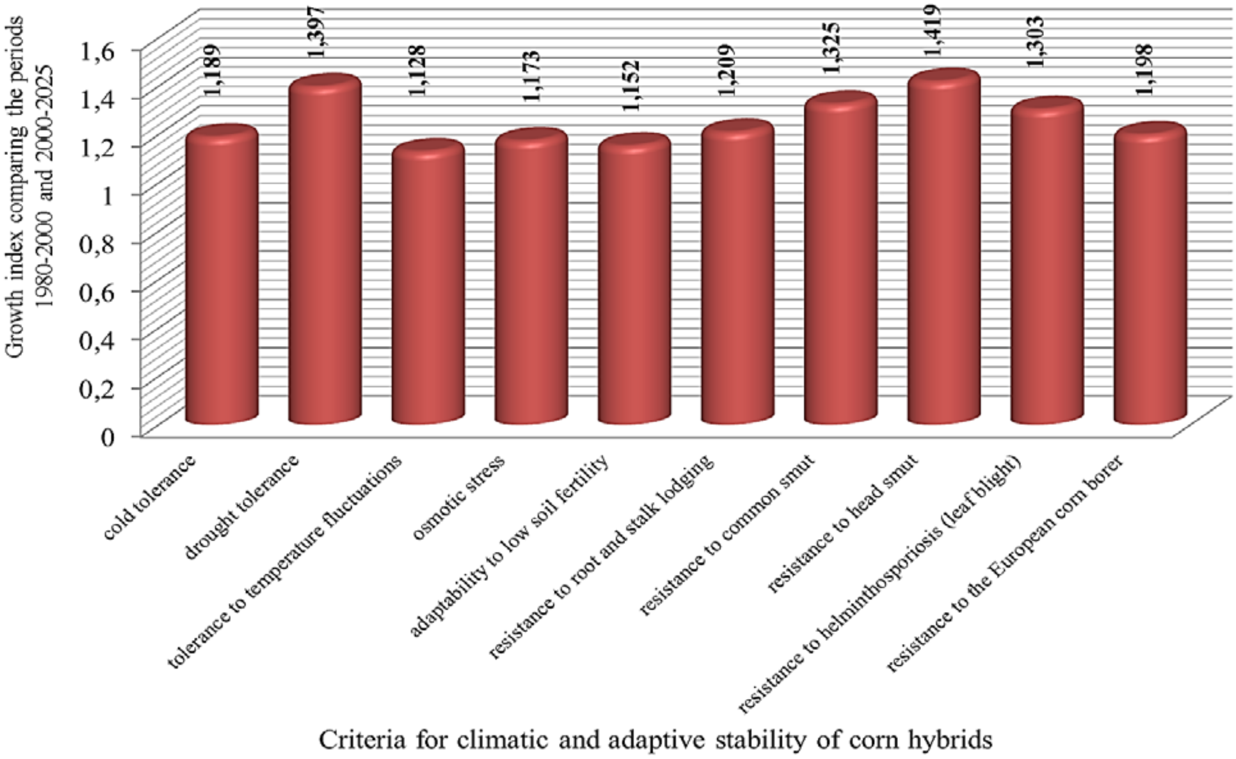

Fig. 3. Comparative dynamics of the adaptive potential of European corn hybrids (1985-2005 vs. 2005-2025) based on basic indicators of zonal agroecological assessment (compiled [31–34] in the growth index expression)

These companies offer high-yielding hybrids adapted to diverse European climatic conditions. The mentioned companies implement their own adaptive breeding programs oriented toward the dynamics long-term projections up to 2050 [6] (Table 1).

Table 1

Content and characteristics of adaptive corn breeding programs of major transnational companies and large European brands (based on [4, 10, 21, 30, 34])

Corporation	Main directions of breeding
KWS	Drought tolerance & ClimaCONTROL3. Under the ClimaCONTROL3 label, KWS offers innovative, drought-tolerant grain corn varieties that derive from a dedicated research and breeding program.
Limagrain	A program of combined adaptability and productivity, multiple trait platforms, herbicide tolerance, insect resistance, high bioproductivity with a rational ratio of above-ground and root biomass, resistance to drought and low temperatures, stability of high grain productivity while maintaining the high-quality biochemical composition of the grain
Syngenta	Corn selection program, highlighted new NK Seeds hybrids for 2025. Syngenta focuses on incorporating desirable traits (insect control, herbicide tolerance, water optimization) into high-performing, diverse, and stable inbred lines. The program uses trait introgression Artesian water optimization technology (hybrids are bred to naturally optimize water use, providing consistent, high yields regardless of weather conditions), Agrisure Technology (Includes Agrisure Duracade (rootworm control) and Agrisure Viptera (above-ground insect control), which offer multiple modes of action against pests like western bean cutworm), Digital Selection Tool (uses AI and decades of data to help farmers select the best hybrids based on field-by-field diagnostics)

Extension of Table 1

Corteva Agriscience	Corn selection program focuses on developing high-yielding, resilient hybrids through advanced breeding, incorporating traits like: Vorceed Enlist; Reduced Stature Corn (evaluated for superior standability and yield, designed to improve resistance to green snap and stalk lodging); Rigorous Testing (PACTS) (hybrid selection involves intensive testing on favorable sites to ensure high dry matter yield and high starch content; Global Research & Local Adaptation (leveraging extensive global germplasm, Corteva adapts hybrids to local, regional conditions, supported by seed production facilities like in Ukraine). Program also uses rigorous testing across various environments to optimize genetic performance, climate resilience, and yield stability
MAS Seed	Corn selection program spans over 60 years, climate-resilient hybrids through advanced molecular markers, data-driven breeding, and extensive R&D trials. Their portfolio prioritizes drought-resistant (WATERLOCK (hybrids specifically bred for superior performance under drought and water-stressed conditions)) and high-quality silage (GREEN+ (Silage corn selected for extended "stay-green" periods, enhancing nutritional value and yield stability under high heat)) varieties designed to adapt to varied European and global climatic conditions. The program aims to create hybrids that are resilient, provide stable yields, and fit into sustainable, regenerative agriculture practices
Euralis (seed brand Lidea)	Corn breeding program on developing high-yield, climate-resilient, non-GMO hybrids, with 17 research stations across Europe, including France, Germany, Romania, Spain, and Poland. Their selection process targets improved water efficiency, drought tolerance ("Stay green" effect). The program utilizes AI-based tools (PREVSEM project) to analyze local weather data and soil types to predict optimal sowing dates, helping to manage risks like cold or water stress. The program, driven by Lidea (a top-six European field seed company), operates 45,000 hectares of production

The top 5 companies (including Syngenta, Limagrain, KWS, Corteva Agriscience) hold half of the maize breeding market. This doesn't directly give counts by brand, but it does confirm thousands of maize hybrids/varieties, with major seed companies controlling the largest shares. These are approximate ranges based on company portfolio patterns, regional catalogs, and industry share data. They represent the breadth of products marketed worldwide rather than an exact count from a single official registry (Table 2). Many companies register different hybrids in different national catalogs (EU countries, US, Latin America, Asia).

Table 2

Summary activity of European companies (Global – approximate)

Company / Brand	Estimated Number of Registered Maize Hybrids
Corteva Agriscience/ Pioneer	~200–400+
KWS	~150–300+
Limagrain / LG Seeds	~150–300+
Syngenta	~150–300+
Euralis (Lidea)	~50–150+
MAS Seeds	~50–120+

Formed by [31, 34].

The following hybrids were identified as leaders of yield level and adaptive potential within the main companies involved in maize breeding and seed production:

Bayer/Dekalb (DKC):
DKC 4964 (FAO 380): 10.96 t/ha
DKC 4490: 10.81 t/ha
DKC 4712: 21.42 t/ha in top-performance trials
DKC 3509: 10.16 t/ha
Euralis/Lidea (ES):
ES Sensor: 10.69 t/ha
ES Concord: 10.05 t/ha
ES Faraday: 6 t/ha (under specific test conditions)

Limagrain (LG): LG 3232 Lupus, LG 30224: Widely used in Northwestern Europe for high forage yield

KWS: Kashmir, Karpatis, Bellavista KXB 643: Recorded high yields in regional evaluations

Other notable performers: Mas 30.K (10.73 t/ha)

The best hybrid portfolio (period 2020–2025) was as follows:

Dekalb: (Bayer) DK 61-88, DK 63-91, DK 6477 (high yield, heat and drought resistance, uniform cob structure, excellent kernel quality. Best suited for grain, feed, ethanol).

Syngenta: (NK Seeds) NK-8840, NK-603 (excellent stress tolerance, insect resistance (Bt gene), good grain quality).

Limagrain: LG 31.250, LG 32.10 (early maturity, drought tolerance, stable performance. Best suited for animal feed, silage, starch production).

Conclusions and Prospects for Further Research. Based on the results, European companies, national breeding centers, and gene banks had a stable trend regarding the development of hybrids with combined abiotic and biotic resistance. These ideotypes were chosen according to the regimes across European countries and partner countries involved in seed distribution and trade.

In evaluating breeding achievements, an average increase in maize hybrid was established at 20.8% adverse environmental factors, including those associated with persistent climate change trends in Europe (drought, low-temperature vegetation regimes with sharp fluctuations) and 29.1% increase in resistance to major biotic stress factors (root and stem lodging, resistance to pathogens and pests).

Prospects for further research: to developed maize hybrid ideotypes based on breeding process typology and the adaptive complex characteristics of applied maize germplasm.

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АНОТАЦІЯ
СЕЛЕКЦІЯ КУКУРУДЗИ ДЛЯ ПІДВИЩЕННЯ АДАПТИВНОСТІ В УМОВАХ ЗМІН КЛІМАТУ ЄВРОПИ

На підставі структурованої статистичної оцінки результатів імплементації селекційних програм кукурудзи Європейського Союзу за параметрами їх спрямованості на забезпечення зростання адаптивного потенціалу сучасних генотипів кукурудзи – сформовано блок узагальнень та тверджень стосовно ефективності даного процесу.

Проаналізовано та деталізовано мережу національних установ та генетико-селекційних центрів Європи, які свою діяльність спрямовують на цільову селекції кукурудзи при застосуванні місцевих рас вихідного популяційного матеріалу за моно- чи полікритеріальним складом стійкісних характеристик до базових стресових факторів, які істотно обмежують реалізацію урожайного потенціалу європейського асортименту високоінтенсивних гібридів кукурудзи. Узагальнено та резюмовано зміст селекційних програм таких відомих європейських брендів у сфері селекції гібридів кукурудзи та ведення зонального та транснаціонального насінництва як KWS, Limagrain, Syngenta, Corteva Agriscience, MAS Seed, Euralis (бренд Lidea). Охарактеризовано зміст даних програм саме з позиції врахування у селекційній практиці стійких кліматичних змін фактичного та прогнозованого масштабу на території Європи та їх масштабування на країни інших територій в тому числі за такими базовими параметрами як посухо- та холодостійкість, жаростійкість та осмотичний стрес, а також комплексом толерантності до найбільш шкодочинних хвороб та шкідників.

Систематизовано за 45 річний цикл оцінок приристну динаміку змін стійкісних параметрів створених гібридів кукурудзи щодо реакції на кліматологічні зміни впродовж вегетаційного періоду генотипів, їх вимогливості до ґрунтової родючості, стійкості до форм вилягання, фітофагів та фітопатогенів з огляду на тісний зв'язок прояву інтенсивності впливу на реалізацію їх біопродуктивності з динамікою змін кліматичних режимів території (температура, зволоженість тощо).

У результуючому підсумку ідентифіковано найбільш вдалі генотипи європейської селекції з позиції кліматологічної адаптивності та абіотичної стресостійкості, які мають європейське та світове визнання, а також придатні для вирощування в Україні.

Ключові слова: *селекція, гібриди, адаптивна стійкість, кліматичні зміни, селекційні програми, абіотичні та біотичні стресфактори.*

Табл. 2., Рис. 3., Літ. 35.

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