UDC: 633.1:631.52:551.583

World practice of breeding adaptive varieties of cereal crops in conditions of climate change

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ARTICLE INFO

Received 26.11.2025
Received in revised form 16.12.2025
Accepted 26.12.2025
Available online 30.12.2025

Keywords:

grain yield stability; stress tolerance; genomic selection tools; marker-assisted selection; genetic engineering; *in vitro* culture; sustainable intensification

ABSTRACT

Grain production is highly sensitive to weather variability, especially to extreme events in terms of their intensity and duration, while individual growth stages differ in their vulnerability to heat, drought, waterlogging and other stressors. The aim of this study is to generalize the contribution of global breeding practice for grain crops, to systematize key approaches to enhancing their adaptive potential, and to outline priority directions for further development under conditions of accelerating climate change. The research is based on general scientific methods of cognition, including system analysis, synthesis, abstraction, generalization, deduction, concretization and formalization. The study summarizes current evidence on how extreme weather factors affect quantitative and qualitative indicators of grain yield and reviews modern breeding strategies aimed at minimising these negative impacts. Particular attention is paid to the development of varieties tolerant to abiotic and biotic stresses, increasing productivity and technological quality of grain, and the introduction of innovative tools such as genomic selection, genetic engineering, marker-assisted selection (MAS) and *in vitro* technologies. It is substantiated that implementing adaptive management in cereal cultivation – through variety choice, optimisation of sowing dates and density, fertiliser systems and crop protection – reduces production risks and costs, stabilises yields and enhances resilience of cropping systems. The results are practically relevant for programmes of development and modernisation of agricultural enterprises specialising in the cultivation of grain crops, where the strategic priority is to combine environmental safety with economic efficiency in line with the European green transition and the global trend towards climate-smart agriculture.

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Citing: Andrushko, M. O., & Andrushko, O. M. (2025). World practice of breeding adaptive varieties of cereal crops in conditions of climate change. *AgroChemistry and Soil Science,* 99, 32-40. doi:10.31073/acss99-04

1. Problem statement

The conditions for growing grain crops are currently very variable, with significant fluctuations in temperature and precipitation during the growing season. Global climate dynamics necessitate the development of a set of hereditary traits of grain crops that are resistant to the effects of climatic factors, which can significantly expand the possibilities for selecting combinations of target traits for optimal genetic adaptation and potential increase in quantitative and qualitative yield indicators. Due to global climate change, with the shift of seasons, plants often suffer both from high temperatures and from insufficient precipitation, or, conversely, from very low temperatures and excess moisture. Such extreme weather conditions can occur at different times during the same growing season. This situation creates certain difficulties for managing grain crops, since a formulaic approach with fixed maps often leads to a significant decrease in yield and, as a result, economic impact. Against this background, a modern approach in agronomy – adaptive management – becomes a viable option. This approach is a system of measures and management decisions that allows you to adapt growing technologies to current and predicted environmental conditions.

The study aimed at studying the possibilities of modern technologies for growing cereals, focused on adaptive management, with the active use of monitoring, modeling and forecasting capabilities. The aspect of breeding adaptive varieties resistant to climate change requires special attention.

Analysis of recent studies and publications. The need to develop, research and implement effective solutions to reduce the negative impact of extreme weather conditions on grain yields currently considered a pressing problem and is present in the current scientific discourse. Numerous works and studies have been devoted to finding optimal solutions in this area; in particular, Zabel et al. [1], Wolfe & Ceccarelli [2], Siddiqui et al. [3], Varshney et al. [4] have paid much attention to this problem in recent publications. The authors emphasize the need for a more in-depth study of the impact of changes in average temperature on the wheat vegetation stage, which should precede consideration of the consequences of extreme weather events and climate change on crop yield indicators.

Vadez et al. [5] and Snowdon et al. [6] studied the impact of global climate change on the process of growing wheat and other cereal crops, paying special attention to the potential for adaptive breeding. Marone et al. [7] and Kom et al. [8] emphasize the possibilities of modern forecasting and modeling using innovative technologies.

Fatima et al. [9] and Fradgley et al. [10] insist that the most effective way to ensure the stability of grain yields under adverse weather conditions is optimal breeding activities by creating stress-resistant genotypes that would adequately respond to the expected frequent extreme weather events and would have high quantitative and qualitative indicators. It is difficult to disagree with this position, because it is breeding that is able to find a large-scale solution to the problem of eliminating the negative impact of weather conditions on the process of growing wheat. Bapela et al. [11] conclude that wheat-breeding models based on adaptive management can help breeding programs identify optimal hypothetical traits for predicting different future scenarios of adverse weather conditions. According to the authors, these models can be effectively use to develop future wheat ideotypes that are resistant to climate change. The results of these studies emphasize the importance of including stress tolerance traits in breeding processes to mitigate the negative impact of global climate change, especially at the regional and local levels, where predicted extreme weather events occur most often.

According to Yanagi [12], the creation of cereal genotypes with a high degree of heat resistance during grain filling is crucial for wheat yield indicators under hotter climatic conditions of the predicted future. Thus, ideotypes of cereal crops resistant to the influence of climatic factors can significantly expand the possibilities for selecting combinations of target traits for optimal genetic adaptation and potential increase in quantitative and qualitative yield indicators.

Despite the relatively high popularity of the studied problem in modern scientific circles of the world community, very few proposals have been develop for practical application in agricultural activities, and they need to be updat in the context of progressive large-scale climate change. It is also necessary to take into account the practical achievements of world breeding experience, which will allow achieving a potential reduction in the negative impact on the quantitative and qualitative indicators of grain crop yield.

Purpose. The purpose of this study is to analyze the existing contribution of world grain breeding practice, to present the main ovative ideas within the framework of the problem under study and determination of vectors for further development of the topic to increase the adaptability of cereals in the conditions of climatic dynamics.

2. Materials and research methods

During the review of literary sources and publications in specialized journals devoted to the topic under study, the primary task was to select relevant and progressive works on the chosen topic to assess the current state of research in this field. The literature selected based on the principle of combining data according to functional criteria, such as productivity, stress resistance and grain quality. Using the generalization method, a set of measures carried out to identify typical features and patterns of the problem under study, opportunities for optimizing the situation and finding the most profitable solutions in economic and environmental aspects. The emphasis placed on the latest developments and research on the problem under study in recent years.

The study based on the hypothetical-deductive method. Assumptions made regarding the feasibility, effectiveness and safety of using modern processes for breeding adaptive varieties in order to prevent a decrease in yield in extreme weather conditions. To confirm this hypothesis, a deductive method used. To determine the effectiveness, features and advantages of specific solutions in the studied process, a system analysis, synthesis and generalization used. The work aimed at active practical application in the future in the process of optimizing the management of risks of reducing the yield of grain crops arising from adverse extreme weather events by increasing the efficiency of selection.

3. Research results

Modern agricultural production still largely based on traditional tillage methods and many years of practical experience in grain farming. However, in the last decades, the technology of grain cultivation has undergone significant changes, and under conditions of global climate change, these changes acquire a strategic character. The main threat to grain cultivation is the increase in the frequency and intensity of local adverse weather events. Climate change first involves a tendency towards higher mean temperatures, shifts in the length of vegetation periods and increased climate variability. At sensitive stages of ontogenesis, grain crops can severely damaged by high temperatures, late frosts, drought or heavy rainfall, which leads to a significant impact on the quantity and quality of the harvest. The impact of these factors at different phases of plant growth has different consequences [13]. For example, heat stress on inflorescence fertility leads to a decrease in the number of grains, and during grain filling, it causes a reduction of grain size and baking or processing quality. Prolonged water stress reduces leaf growth, accelerates leaf senescence and shortens the effective photosynthetic period. Extreme drought episodes during grain filling reduce plant growth, leading to crop failure, whereas drought during reproductive development primarily affects quantitative yield indicators. Excessive precipitation during plant maturation leads to partial loss of the crop, pre-harvest sprouting and a decline in quality parameters [5].

An increase in the frequency and intensity of such adverse weather events poses a greater risk than gradual average climate change, since the time available for biological and technological adaptation significantly reduced. In this regard, much attention has recently been paid to the study of adverse weather conditions in climate modelling systems for agricultural grain crops and to the improvement of breeding methods for the development of resistant adaptive varieties that can maintain productivity in unstable environments.

Adaptive management of grain crops based on the identification of key environmental factors at different stages of growth that affect quantitative and qualitative yield indicators. By choosing adaptive management, agricultural producers are able to regulate a maximum number of influencing parameters — from the choice of variety, sowing date and rate, the amount, timing and form of fertiliser application to the use of growth regulators and plant protection products — in order to optimise quantitative and qualitative yield indicators [14]. In practice, this means moving from fixed technological schemes to flexible, scenario-based decisions, which regularly updated according to monitoring, and forecasts.

One of the effective tools used in modern grain-growing technologies is the active use of climate and crop models to predict weather conditions and crop responses. These models allow selecting the optimal parameters of sowing rate and timing, as well as nitrogen application, depending on predicted temperature and precipitation patterns. The use of nitrogen in differentiated doses and terms helps to reduce the stressful impact of low temperatures on the plant, promotes growth during warmer periods of vegetation, and has a positive effect on the development of the plant root system during periods of high humidity and low temperatures [7]. At the same time, by adjusting the timing of nitrogen application, it is possible to delay plant growth and development, which is important for preventing early heading and ear emergence that may expose crops to late spring frosts, and thus indirectly affects yield indicators.

The global practice of breeding adaptive varieties of grain crops focused on the creation of varieties with increased resistance to stressful weather conditions, such as drought, heat, soil salinisation or periodic waterlogging. For this purpose, both traditional breeding methods and modern genetic technologies are successfully used. The main approaches focused on creating high-yielding varieties with improved grain quality that best meet local growing conditions and are able to realise their potential under a wide range of seasonal scenarios [15]. At the same time, breeding programmes increasingly guided by explicit ideotypes – conceptual models of a “desired” plant combining a set of morphological, physiological and phenological traits adapted to target environments.

The main vectors of breeding practice in this context are as follows:

1) Breeding varieties resistant to abiotic stresses,

2) Breeding varieties resistant to biotic stresses,

3) Increasing productivity and improving grain quality,

4) Systematic use of innovative biotechnological tools that accelerate the breeding cycle.

Breeding varieties resistant to abiotic stresses involves increasing the adaptive capabilities of crops for drought tolerance (for example, developing wheat or maize varieties that maintain productivity under moisture deficit in arid and semi-arid regions). Also important are frost resistance (overcoming the critical barrier of low temperatures during wintering or early spring growth), salt tolerance (breeding cereal varieties that can grow and yield at elevated soil salinity levels, particularly in irrigated areas with secondary salinization), and resistance to short-term floods and heat waves. For example, in Australia significant attention is paid by breeders to breeding wheat varieties that use water more efficiently in arid conditions, whereas in China large-scale breeding projects for rice varieties able to grow on saline soils are being implemented [2; 10]. These examples demonstrate that abiotic stress tolerance increasingly considered not as an additional trait, but as a central breeding goal in regions highly exposed to climate risks.

Breeding of cereal varieties resistant to biotic stresses involves the integration of genes for increased resistance to pests and diseases (Septoria leaf blotch, Fusarium head blight, rusts and other pathogens). The process is carried out mainly using molecular genetic methods and modern biotechnologies and is aimed at identifying resistant genotypes, reproducing hybrids by crossing and selecting the best offspring. Resistance to biotic stresses also includes improved tolerance to herbicides, which allows more effective weed control and reduces competition for water and nutrients. In particular, in the USA corn varieties with increased yield indicators and combined resistance to herbicides and pests are particularly widespread [4; 15]. Under climate change, such resistance becomes even more important, as warmer conditions and altered precipitation regimes may modify the spectrum and aggressiveness of pathogens and pests.

Another direction of grain breeding is to improve the quality and productivity of grain, including the optimisation of nutritional value by increasing the content of proteins, essential amino acids, vitamins and microelements. In the process of breeding varieties that provide higher yields per unit area, it is important to use modern technologies successfully applied in world practice. Among them, genomic selection, genetic engineering and marker-assisted selection (MAS) are the most effective [6]. These technologies make it possible to simultaneously take into account a large number of loci associated with adaptive and quality traits and thus accelerate the accumulation of favourable alleles in breeding material.

The advantages of the genomic selection method, which involves large-scale analysis of genomes for accurate selection of the best samples for further crossing, are the avoidance of lengthy phenotypic tests, reduction of time costs, increased accuracy of selection in the early stages of plant development, as well as the possibility to work directly with genetic information. Examples of global genomic breeding experience include hybrid forms of maize with increased resilience to drought, high-yielding varieties of rice and wheat adaptable to adverse growing conditions, and creation of new populations with optimised root systems for better water and nutrient uptake under drought stress [4].

Genetic engineering involves the integration of genes from other organisms to form new resistant traits. Examples of global genetic engineering practice in grain crop breeding include herbicide-resistant maize and soybean, which are widely grown in the USA and some other countries. Thus, up to 80% of maize crops and 95% of soybean crops in the USA genetically modified for resistance to herbicides and pests. Another well-known example is modified “golden rice” with an increased content of beta-carotene aimed at improving human nutrition [6]. Although the spread of genetically modified cereals remains limited by regulatory and public acceptance factors in many countries, the knowledge gained through such projects actively used in conventional and marker-assisted breeding.

The use of in vitro tissue and organ culture, a biological system that lacks the regulatory mechanisms inherent in the whole organism, is becoming particularly relevant in global practice. The in vitro method is now widely used to solve applied problems in breeding various agricultural plants, including cereals: screening and identification of resistant forms, rapid propagation of valuable genotypes, and studying the response of cells to the toxicity of selective agents [3; 12]. In particular, in vitro systems enable the selection of callus cultures and regenerants tolerant to salinity, drought imitating agents or certain pathogens, which can used as a source material in breeding programmes.

The main feature of breeding for adaptability is systematic control of environmental plasticity, stability and adaptability of varieties and hybrids already at the early stages of the breeding process. Progress in agriculture in the near future will be determin by improved adaptation of agricultural systems and agrolandscapes to environmental factors that change in time and space. Therefore, modern breeding approaches are characterised by an agroecological focus associated with greater adaptability of new varieties and hybrids to local conditions, as well as by science-intensive cultivation technologies. Their main distinguishing feature is the combination of high potential productivity (crop size and quality) with resistance to the most common abiotic and biotic stressors in the region and a favourable genotype × environment interaction profile. The effectiveness of such selection achieved with various methods for assessing ecological plasticity and stability, which differ in the complexity of calculations and interpretation of results but provide breeders with quantitative criteria for comparing genotypes across multiple environments.

To better systematise the directions of current practice in adaptive breeding and management of cereal crops, the main approaches and expected effects can be summarised as follows (Table).

In order to obtain highly adapted genotypes for each specific location, it is necessary to solve a number of interconnected methodological problems. First, breeders must clearly determine the mechanisms of varietal response to changing environmental conditions at different organisational levels – from physiological (water-use efficiency, photosynthetic activity, root growth dynamics) and morphological (plant height, leaf architecture, root system architecture) to phenological (duration of vegetative and reproductive phases, thermal requirements). Second, it is essential to select the most informative traits and properties as targets for selection: not only result in the form of grain yield, but also secondary traits that more closely linked to tolerance (e.g. stay-green, early vigour, canopy temperature, grain-filling duration) and can measured reliably in multi-environment trials. Third, effective methods for evaluating breeding material must identified, combining classical yield trials with stress screening, remote sensing indicators and model-based analysis. Finally, representative environments (locations and years) have to chosen so that the whole range of target stress scenarios – typical, moderately extreme and rare but critical – is covered and genotype × environment (G×E) interactions can be reliably quantified.

Table
Main directions of adaptive breeding and management of cereal crops under climate change

Direction / approach	*Dominant target stressors*	*Tools and technologies used*	*Expected effect on yield and stability*	*Illustrative examples of application*
Breeding for abiotic stress tolerance	Drought, heat, frost, salinity, temporary flooding	Conventional hybridisation, selection in stress environments, landrace use, genomic tools	Maintenance of yield in dry and hot years; expansion of production into marginal areas	Drought-tolerant wheat and maize in Australia; salt-tolerant rice in China
Breeding for biotic stress resistance	Fungal diseases, pests, weeds	Disease nurseries, molecular markers, pyramiding resistance genes, herbicide tolerance	Reduction of yield losses and pesticide costs; greater predictability of production	Rust- and Fusarium-resistant wheat; insect-resistant maize
Improvement of grain quality and nutritional value	Protein deficit, micronutrient deficiencies	Selection for quality traits, MAS for quality loci, biofortification programmes	Higher added value of grain, better processing quality and nutritional profile	High-protein wheat, biofortified cereals (e.g., pro-vitamin A “golden rice”)
Genomic selection and digital breeding	Complex polygenic traits	Dense molecular markers, genomic prediction models, big data and machine learning	Acceleration of breeding cycles; precise accumulation of favourable alleles	Genomic selection in wheat and barley programmes in Europe and Australia
In vitro and biotechnological tools	Low regeneration capacity, slow propagation	Tissue culture, somaclonal variation, micropropagation, cell selection under stress agents	Rapid multiplication of elite genotypes, creation of stress-tolerant lines	In vitro selection of salt- and drought-tolerant lines in cereals
Adaptive crop management (agrotechnology)	Intra-seasonal weather variability	Crop and climate models, remote sensing, variable rate technology, decision support systems	Optimisation of sowing dates, densities and fertiliser regimes; reduced risks	Adjustment of sowing windows and N-rates based on seasonal forecasts

In this context, Table summarises the main current directions of adaptive breeding and crop management for cereals under climate change. The first two rows reflect primarily genetic strategies – breeding for tolerance to abiotic stresses (drought, heat, salinity, frost, temporary flooding) and for resistance to biotic stresses (diseases, pests, weeds) – and show how different combinations of conventional hybridisation, stress-environment selection and molecular tools are used to maintain yields and reduce losses. The next two rows characterise more advanced breeding approaches: improvement of grain quality and nutritional value through biofortification and selection for technological traits, and the use of genomic selection and digital breeding to accelerate cycles and work with complex polygenic traits. The last two rows focus on biotechnological tools (in vitro systems for rapid propagation and stress selection) and adaptive crop management (climate and crop models, variable-rate fertilisation, decision support systems), highlighting that genetic progress must be complemented by flexible agrotechnology. In aggregate, the table illustrates that effective climate adaptation achieved not through a single "silver bullet" solution, but through an integrated package of genetic, biotechnological and management decisions, tailored to the specific stress profile of each region.

In developed countries it is estimated that 90–95 % of yield increases over the past decades have been achieved through genetic improvement of varieties and hybrids, and only 5–10 % through improved agricultural technologies alone [5; 9]. This further underlines the central role of breeding in long-term adaptation strategies. At the same time, such figures do not diminish the importance of agronomic optimisation; rather, they indicate that technologies like fertilisation, plant protection or irrigation fully realise their potential only when combined with genetically improved, stress-tolerant varieties. Consequently, the methodological toolkit of adaptive breeding increasingly based on multi-environment trials, in which genotypes evaluated simultaneously across a wide range of locations and years. Statistical models of G×E interaction and stability/plasticity indices allow breeders to distinguish between genotypes that show high performance only in favourable conditions and those that maintain yield under stress, which is crucial for climate-risk-prone regions.

In all cereals, varieties that are resistant to lodging and adverse conditions are particularly valued, because lodging not only reduces yield but also complicates harvesting and worsens grain quality. The introduction of short-stem varieties of wheat with a stronger culm, including those carrying semi-dwarf genes, has made it possible in Mexico, India and several other countries to significantly increase wheat grain production over the past 15–20 years and, in some cases, to completely abandon imports. In parallel, breeding programmes in other regions have focused on maintaining sufficient straw strength for high nitrogen and irrigated systems, where biomass is greater and lodging risk is higher. Depending on regional conditions, early-maturing, drought-resistant and winter-hardy varieties may be required, as well as varieties suitable for cultivation on both irrigated and drained land [1]. In continental climates with frequent spring frosts, priority given to genotypes with flexible phenology and frost resistance; in Mediterranean-type climates – to deep-rooted, drought-tolerant varieties; in areas with mild, humid winters – to varieties resistant to winter diseases and waterlogging.

The development and productive use of low-yield lands (acidic, saline, marshy and sandy soils) also depends on the success of breeding. On acidic soils, breeders select varieties with increased aluminium tolerance and efficient phosphorus uptake; on saline soils – genotypes capable of excluding or compartmentalising toxic ions; on sandy and shallow soils – varieties with root systems adapted to low water-holding capacity. In some countries, special attention is paid to this aspect at the regulatory level. For example, in Brazil varieties sensitive to acidic soils are not allowed for production, which demonstrates the integration of breeding decisions into national regulatory frameworks and land-use policy [7; 11]. Such regulatory measures stimulate both public and private breeding programmes to focus on adaptability traits that are most important for national agroecosystems and long-term soil fertility.

Thus, adaptability is a crucial property of promising cereal varieties that must be consistently taken into account in breeding programmes, starting from the earliest stages of selection. At the same time, attention should be paid to the deliberate choice of growing environments for each variety and hybrid, taking into account the role of G×E interactions and the concept of target production environments or "mega-environments". Using the existing set of methods for determining potential productivity and adaptability – including multi-environment yield trials, stability and plasticity parameters, and model-based scenario analysis – as well as modern tools for assessing the stability and plasticity of crop varieties, it is possible to establish the reliability of observed differences and obtain the necessary information for selecting valuable starting material for breeding for adaptability. Integrating this information into adaptive management systems at the farm and regional levels, and linking varietal recommendations with seasonal forecasts and decision support tools, creates prerequisites for a transition to climate-smart agriculture capable of maintaining grain yield stability and economic viability under conditions of increasing climate risks.

4. Conclusions

Global climate change necessitates the development of grain varieties that are resistant to the effects of climatic factors and extreme weather conditions, which can significantly expand the possibilities for optimal genetic adaptation and a potential increase in quantitative and qualitative yield indicators. Effective implementation of adaptive management in grain growing allows reducing costs, increasing yields, minimizing the need for repeated fertilizer applications, and increasing plant resistance to pests and external factors. The main vectors of breeding practice in this context are the development of varieties that are resistant to abiotic and biotic stresses, increasing productivity, and improving grain quality. Among the most effective innovative technologies of breeding activities are genomic breeding, genetic engineering and marker-assisted breeding (MAS), as well as in vitro methods.

Further research is need into the possibilities and development of an algorithm for an agroecological monitoring system within the spectrum of influence of global climate change and extreme weather events at the regional and local levels, taking into account progressive breeding opportunities. Only an integrated approach that takes into account regional and local zoning, together with multifunctional agroecological monitoring, can not only mitigate the negative impact of adverse weather conditions on grain cultivation, but also ensure the sustainability of economic returns from activities and reduce anthropogenic impact against the background of global climate risks.

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УДК 633.1:631.52:551.583

Світова практика селекції адаптивних сортів зернових культур в умовах зміни клімату

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Отримано 26.11.2025; Доопрацьовано 16.12.2025; Затверджено 26.12.2025; Доступно online 30.12.2025

Анотація. У статті проаналізовано світовий досвід селекції адаптивних сортів зернових культур в умовах зміни клімату та окреслено ключові напрями модернізації селекційних програм. Обґрунтовано, що зростання частоти екстремальних погодних явищ (посухи, теплові хвилі, весняні приморозки, надмірні опади) висуває на перший план завдання підвищення екологічної пластичності та стабільності сортів, тоді як традиційна орієнтація лише на потенційну врожайність стає недостатньою. Показано, що у провідних аграрних країнах 90–95 % приросту врожайності забезпечено за рахунок генетичного удосконалення сортів і гібридів, тоді як частка суто агротехнічних чинників є відносно меншою, що підкреслює стратегічну роль селекції в адаптації зерновиробництва до кліматичних ризиків. Розкрито основні вектори сучасної селекції зернових: підвищення толерантності до абіотичних стресів (посуха, спека, засолення, перезволоження, низькі температури), формування стійкості до біотичних факторів (хвороби, шкідники, бур'яни), поліпшення якості та харчової цінності зерна, а також широке впровадження геномної селекції, маркер-асоційованого добору, біотехнологічних підходів та in vitro систем. Окрему увагу приділено інтеграції селекційних рішень з адаптивним управлінням посівами — використанням моделей урожайності й клімату, диференційованого внесення добрив, цифрових платформ підтримки прийняття рішень. Узагальнено методичні виклики, пов'язані з добором інформативних ознак, плануванням багатомісцевих випробувань, кількісною оцінкою взаємодії генотип × середовище та виділенням генотипів із поєднанням високої продуктивності й стабільності. На основі аналізу світової практики зроблено висновок, що формування адаптивних сортів зернових культур є ключовою умовою переходу до кліматично орієнтованого (climate-smart) землеробства. Комплексне поєднання генетичних, біотехнологічних та агротехнологічних рішень створює передумови для збереження врожайності й якості зерна за умов зростання кліматичних ризиків та більш інтенсивного використання маргінальних земель (кислих, засолених, піщаних, перезволожених ґрунтів). Отримані узагальнення можуть бути використані для коригування національних селекційних програм, розробки рекомендацій щодо цільових середовищ вирощування та інтеграції селекційних пріоритетів у нормативно-правову базу аграрного сектору.

Ключові слова: зернові культури; адаптивні сорти; селекція; зміна клімату; абіотичні стреси; біотичні стреси; геномна селекція; адаптивне управління посівами.

Форма цитування: Andrushko M. O., Andrushko O. M. (2025). World practice of breeding adaptive varieties of cereal crops in conditions of climate change. *AgroChemistry and Soil Science,* 99, 32-40. doi:10.31073/acss99-04