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ANALYTICAL REVIEW OF THE BREEDING ASPECTS IN DEVELOPMENT OF THE FACULTATIVE WHEAT

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SUMMARY

With climate change and global warming, a specific place is necessary for the selection of facultative soft wheat, as this crop has increased plasticity and adaptability to environmental conditions compared with the winter and spring wheat. In facultative wheat breeding, the use of classical methods can be via standard selection and sowing of hybrid populations alternately in autumn and spring. Facultative hybrid populations comprised facultative x facultative genotypes, winter x spring cultivars, and spring x winter cultivars. The duration of 'germination-earing' can serve as an additional indicator for selection and types of crossing: facultative x winter cultivars and spring x winter cultivars were the decision in breeding for better productivity. In seed production and to preserve the economically valuable properties of a facultative cultivar, it is necessary to use the 'halves' method. Facultative wheat is superior to winter sowing and has low sensitivity to vernalization but highly sensitive to photoperiod. However, few past studies carried out on facultative wheat breeding used modern biological methods and techniques. The production of facultative wheat is mainly a task carried out by the Krasnodar Territory (Russia) and the Republic of Kazakhstan. In 2023, in the south and southeast of the Republic, the area sown with facultative wheat of the Kazakhstanskaya 10 variety amounted to 28,953.8 hectares.

Keywords: Facultative soft wheat, selection, photoperiodism, molecular markers, production

Key findings: This review article interprets the facts of facultative breeding materials obtained through classical selection and the cultivars developed in Russia, Armenia, Georgia, Kyrgyzstan, Turkey, New Zealand, and in South-East Kazakhstan, actively involved in production

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INTRODUCTION

The world's population will exceed nine billion, and this will lead to an increased demand for food by 2050. Wheat is the major staple crop, and its production play a vital role in food security. The leading wheat producers are the USA, China, India, Russia, Canada, Australia, Ukraine, Pakistan, Turkey, Argentina, Iran, and Kazakhstan. According to the forecast in 2023–2024, the worldwide wheat production was 789 million tons, which was 7.9 million tons more than the previous year 2022–2023 (URL https://www.fao.org/worldfoodsituation /csdb/ru).

Kazakhstan's most crop lands sit in the risky farming zone (Northern Kazakhstan) with low annual precipitation (150–320 mm). Spring soft wheat, with the highest economic value dominating the total wheat production (15.5 million tons), has its main production in the northern regions of Kazakhstan. Winter wheat growing prevails in the southern regions of the country, and its total share of production is 0.3 million tons of grains. The level of winter hardiness compared to winter wheat received an average assessment (Yesimbekova, 2014; Kushanova *et al.,* 2023; Aidarbekova *et al*., 2024). Currently, the Republic of Kazakhstan is one of the six world exporters of wheat and ranks third in the CIS (Customer Information System) market in grain production, as one of its largest exporters.

Over the past decades, a global warming trend has prevailed (on average, about 1.8 °C per 100 years), which was two-times higher than global values. For the successful cultivation of cereal cultivars with a good harvest requires attention to ecological plasticity, resistance to low and high temperatures, excess and lack of moisture, as well as, various diseases and pests, which are important (Yesimbekova, 2014).

One of the solutions to these problems is the study of facultative forms of wheat, with their cultivation possible on both winter and spring crops, which can make it obtain a guaranteed harvest. Thus, in Armenia, the selected varieties gave good results for biological and yield indicators, both in winter crops in the Ararat plain, and in spring crops in the mountainous zone of the Republic (Barbaryan *et al*., 2020). Currently, as a result of the selection of this crop, several varieties of facultative wheat have reached creation and approval for use in production, developed and introduced in the conditions of Russia, Kyrgyzstan, Kazakhstan, Turkey, and New Zealand.

Facultative wheat has advantages over winter and spring crops due to its genetically determined enhanced plasticity and adaptability, which authenticated them as a more popular crop for production (Neugschwandtner *et al*., 2015; Filobok *et al*., 2016). Consequently, the selection of new high-yielding cultivars of facultative wheat is relevant and in demand today.

RESULTS AND DISCUSSION

Selection of facultative wheat worldwide

Among grain crops, including wheat, its different types exist with varied development, i.e., winter, spring, and facultative (Aitymbetova *et al.,* 2011; Yesimbekova, 2014). Facultative wheat sowing, unlike typical spring and winter crops, can be in autumn or spring, while the former yields a harvest only when sown in spring, and the latter only when sown in autumn (Filobok *et al.,* 2016; Keser *et a*l., 2020). Breeding work on facultative wheat in the CIS started in 1993 in Krasnodar – National Grain Center named after P.P. Lukyanenko and still continues today (Filobok *et al*., 2010; 2014a, b). As a result, in Russia, the development of facultative wheat varieties includes the following:

— *Lastochka* cultivar — zoned in 2005, is suitable for winter and spring sowing. In winter and spring sowing, its grain yield is 7.5–8.0 and 6.0–6.5 t/ha, respectively, which is 1.5–2.0 t/ha higher than the other zoned cultivars of spring wheat;

— *Athena* — zoned in 2009, more frost-resistant than the cultivar *Lastochka*, with the highest grain protein, and also resistant to fusarium head blight;

— *Pallas* — with frost and winter hardiness, closer to the cultivar *Bezostaya-1*. It has a yellow shade of the bread crumb caused by the *Y* gene. It is also a carrier of the leaf rust resistance gene *Lr 19*, closely linked with the stem rust resistance gene *Sr 25*, effective against the Ug race 99, transferred from *Ag. Elongatum;*

— *Anka* — a drought-resistant cultivar. On grain productivity, it is advantageous over the standard cultivars. Consistently observed with the highest protein content (18.5%) and gluten (35%), ensuring the highest nutritional value of bread made from its flour, and

— *Velena* — characterized consistently by the highest productivity at different times of autumn and spring sowings, and is also capable of generating enhanced yield (10 t ha^{-1}).

The optional cultivar *Intensivnaya* has succeeded development at the Kyrgyz Research Institute of Agriculture, Kyrgyzstan. The said cultivar became zoned since 1978, suitable for autumn and spring sowings in rainfed and irrigated conditions, as well as, in the regions of secured rainfed land of Uzbekistan and the northeastern zone of Armenia (Satybaldin, 2001). In past years, other facultative wheat cultivars of the institute have served in production, i.e., *Jamin*, *Araket*, *Kasiet*, *Dank*, *Wassan,* and *Nazdan* (Kyrgyzstan) (Pakhomeev *et al*., 2023). In Armenia, environmental trials of six optional varieties yielded better results for biological and economic performance, with two accessions identified as 950129 and 060050 (Gukasyan *et al*., 2022).

In Kazakhstan, the *Krasnaya Zvezda* was the first cultivar of facultative wheat, developed at the Agricultural Experimental Station (Krasnovodopad). In the 1950s and 1960s, sowing of the said cultivar reached an area of 300,000 hectares in the south of Kazakhstan and Uzbekistan. Another optional cultivar of this station is *Pamyat-47*, which commenced zoning since 1995 in the southern regions of Kazakhstan. The cultivar *Kazakhstanskaya-10*'s development was a joint venture with the Kazakh Research Institute of Agriculture and the Semipalatinsk Agricultural Experimental Station. Its zoning began since 1990 in Kyrgyzstan, since 1992 in Kazakhstan, and also in Bashkortostan in Russia. The facultative wheat cultivar *Egemen*, developed at the Kazakh Research Institute of Agriculture and Plant Growing, attained approval for use since 2006 in the southern regions of Kazakhstan. Facultative wheat cultivation is prevalent in Almaty, Zhambyl, South Kazakhstan, Turkestan, and Zhetysu regions, with mild soil and climatic conditions in winter (Satybaldin, 2001).

The selection results of facultative cultivars of soft wheat are also available in non-CIS countries. Thus, in Turkey, the new facultative wheat cultivar, *Taisa*, sown on March 15, exceeded the typical spring cultivar *Pedureni* by 419 kg/ha, showed better potential and important progress in wheat breeding (Keser *et al.,* 2020). Under the conditions of Erzurum, Turkey, an optional cultivar *Turkmen*, with high productivity and white grains, bore isolation and recommendation for this region (Özcan *et al.,* 2021). Meanwhile, *Aquilla*, a cultivar developed by the Crop and Food Research Institute, New Zealand, is suitable for sowing from May to October in Canterbury, New Zealand, and in the southern part of the North Island in spring. There, it produces the same yield as the standard spring wheat *Kohika*. The said facultative wheat cultivar also emerged resistant and moderately resistant to most common leaf diseases and pre-harvest sprouting, respectively (Shorter *et al.,* 2005).

Facultative wheat breeding with methodological aspects

In the facultative wheat breeding, classical breeding methods, such as, the use of source material, followed by crossing and selection, have been progressive. However, as a basis of breeding research, the source material is well-studied. Regarding this, the Kazakh Research Institute of Plant Growing and Agriculture, studying the collected germplasm from international nurseries FAWWON STEMRRSN, WWEERYT, RWKLDN, HLWWC, TCI, IWN, and NWWCAT, has identified numerous genotype sources with economically valuable traits for the facultative wheat selection (Nurpeisov, 2019).

An analysis of the selection of facultative wheat cultivars indicated many of their development was mainly by crossing winter and spring wheat cultivars (Satybaldin, 2001; Filobok *et al*., 2010). However, in Southeast Kazakhstan, facultative hybrid populations manifested in different types of crossing, i.e., facultative x facultative cultivars, facultative x winter cultivars, facultative x spring cultivars, and spring x winter cultivars (Nurpeisov and Dauletov, 2021).

An observation also revealed in hybrids of spring and winter wheat, two-handed recombinants should inevitably arise (genotypes Vrn Vrn Ppd Ppd, and Vrn Vrn Ppd Ppd), in which, recombining the two genetic systems under consideration occurred, i.e., dominant Vrn alleles (as in spring) combined with recessive ones Ppd alleles (as in winter). Thus, in the experiments on crossing the spring wheat cultivar *Moskovskaya-21* with winter cultivar *Erythrospermum-998*, the offspring appearance (starting from F_2) of such recombinants were two-handed (Agamalova *et al.,* 1988).

Knowingly, the growing season period is of great importance in the selection of wheat cultivars of different maturity periods. Evidently, when sowing transpired in autumn, facultative cultivars and hybrids of wheat generally ripen 6–7 days earlier than winter cultivars sown in spring, and on contrary, 5–7 days later than spring wheat cultivars. Consequently, identifying facultative lines from a hybrid population by the number of days before heading can serve as an additional indicator of selection in Kazakhstan (Nurpeisov and Dauletov, 2021).

A similar phenomenon was also noticeable by studying cultivars and lines of facultative wheat obtained from the international selection. Assumingly, in the first case, this corresponded to their physiological characteristics as forms with a short period of vernalization during autumn sowing, and in this connection, with a faster pace of development. However, in the second case forming with a strong photoperiodic reaction, the spring sowing leads to late heading in the conditions of Southeast Kazakhstan (Yesimbekova, 2010; Yesimbekova *et al.*, 2022).

From studies of facultative soft wheat of the international selection under conditions of autumn and spring sowing in the foothill zone of the Zailiyskiy Alatau, the winter sowing showed superiority for manifesting various components of productivity. Thus, during spring sowing, facultative cultivars reduced plant height and ear length to 20%, the number of spikelets per spike to 15%, the number of grains per spike and grain weight per spike to 12% compared with autumn sowing (Yesimbekova, 2010). However, a significant increase in the technological indicators of grains with spring sowing was also evident in the research of the Federal State Budgetary Scientific Institution – National Grain Center named after P.P. Lukyanenko (Filobok *et al*., 2014a, b).

Research has also established, with autumn and spring sowing in Southeast Kazakhstan, the selection efficiency of productive lines of facultative bread wheat is higher in hybrid populations (F_2 – F_4). These came from the crossing of facultative by winter cultivars and spring by winter cultivars. In such wheat lines, the yield ranges from 4.04 to 4.84 t/ha in autumn, and from 2.67 to 3.38 t/ha in spring sowing, exceeding the yield of the standard cultivar Kazakhstan-10 by 0.21–1.05 and 0.24–0.95 t/ha, respectively. Consequently, the indicated types of crossing were more decisive in the selection of productive cultivars of facultative bread wheat (Nurpeisov, 2021).

By breeding two-handed wheat cultivars, it is crucial the genotypes must remain stable in a wide range of weather and environmental conditions (Filobok *et al*., 2010). For the selection of such genotypes in the Krasnodarsk, the National Grain Center named after P.P. Lukyanenko used the natural selection, sowing hybrid populations alternately in autumn and spring, with the selected lines sown in autumn and spring. The optimal height of two-handed facultative wheat cultivars for autumn sowing should not exceed 100 cm. Otherwise, problems with resistance to lodging arise, and reducing the height below 80 cm during spring sowing leads to decreased grain productivity (Filobok *et al*., 2010, 2014a, b).

In preserving the economically valuable properties of a facultative cultivar, a different approach to primary seed production is necessary over the seed production in winter and spring wheat. Therefore, we need a separate method for alternative assessment of seed nurseries, alternating autumn and spring sowings, using the 'halves' method (Bespalova *et al*., 2011).

Facultative wheat response to vernalization and photoperiodism

Response to photoperiodism (Ppd) and vernalization (Vrn) are important adaptive mechanisms, enabling winter crop plants to survive in winter at less differentiated stage of development and make the fullest use of favorable conditions during spring-summer growing season (Fait, 2006). It was also notable, the main part of the diversity in the growing season length, particularly, in the number of days before heading, resulted from differences in the *Vrn* gene system (up to 75%). About 20% of the differences are due to the diversity in Ppd loci and alleles. The remaining 5% of the differences had no association with systems for controlling vernalization sensitivity and responsiveness to photoperiod and correlated to the systems of precociousness genes (Stelmakh, 1984, 1986). Two-handed cultivars should differ from winter cultivars in the genetic system of both *Vrn* and *Ppd* genes, which should be less sensitive to vernalization, however, respond quite considerably to short days, limiting the development (Bespalova *et al.*, 2010).

Currently, four gene systems affecting the development rate have been distinct in common wheat (*Triticum aestivum* L.), i.e., response to vernalization (Vrn), response to photoperiod (Ppd), control of early ripening (Eps), and control of vernalization duration (Vrd). Moreover, five known *Vrn* genes exist, i.e., *Vrn-A1, Vrn-B1, Vrn-D1, Vrn-D4*, and *Vrn-B3*, for which determining localization has been successful. The first three genes appeared on the 5th chromosome of each common wheat genome, i.e., 5A L, 5B L, and 5D L. The *Vrn-D4* gene location is on chromosome 5D, and *Vrn-B3* on chromosome 7BS (Yan *et al*., 2006; Yoshida *et al.,* 2010; Koksharova, 2012).

In the Ppd system, the known three genes are in the second chromosome of each genome (*Ppd1-2D*, *Ppd2-2B*, and *Ppd3-2A*). Winter types have recessive alleles for all these three genes (*Vrn, Vrn Ppd,* and *Ppd*). However, the spring types have at least one dominant gene (*Vrn-Ppd*). Diplopods (Vrn-PpdPpd) have dominant alleles from *Vrn* and recessive alleles for all the three *Ppd* genes. Thus, diplopods of wheat differed from winter cultivars by the presence of a dominant allele of the Vrn2 locus in their genotype. These genotypes also differed from the spring wheat, and in that, the location of *Vrn2* gene is in their gene pool sensitive to the photoperiod. Increased winter hardiness in diplopias and a significant delay in their development in the autumn period succeed due to the interaction of two genetic systems in the homozygous genotype Vrn1, Vrn2, Vrn3, Ppd1, Ppd2, and Ppd3. In this case, the completely recessive genotype for vrn1-3, regardless of the *Ppd* genes, determines the winter hardiness. Spring genotypes will be those dominant for the *Ppd* gene and possessing the dominant *Vrn1* gene, in combination with any alleles of the remaining Vrn loci.

Facultative wheat with molecular study

The introduction of advances in molecular markers' technology are active in breeding programs worldwide. It allows direct genotypes' selection, hastening the development of new crop cultivars with desirable properties (Bespalova *et al*., 2012; Leonova, 2013; Davoyan *et al.*, 2014; Zaitseva and Lemesh, 2015; Baidyussen *et al*., 2024).
Currently, actively developing the molecular marking of the *Vrn* and *Ppd* genes is also ongoing for implementation in wheat breeding, including the development of facultative types. Given the combination of recessive and dominant alleles of these loci correlated with the type of development of wheat, and their identification by classical breeding methods without using DNA technology is difficult. Thus, less sensitivity to vernalization and high

sensitivity to photoperiod are the characteristics of true two-handed due to the recessive alleles found in the *Vrn-A1, Vrn-B1* genes and the dominant allele of the Vrn-D1 locus, reducing the need for vernalization (Filobok *et al*., 2016).

Dominant alleles of the *Vrn-B1* and *Vrn-D1* genes do not always determine the spring type of development, and can also occur in genotypes with a facultative type of improvement (Sun *et al*., 2009). Thus, the study of the facultative wheat cultivar *Anka* at the All-Russian Research Institute of Plant Growing named after N.I. Vavilov (St. Petersburg) confirmed its low sensitivity to vernalization and high sensitivity to photoperiod. Molecular testing of the alleles of the *Vrn* and *Ppd* genes revealed the presence of a recessive allele of the *Ppd-D1* gene, which determines the highest photosensitivity. Meanwhile, the presence of recessive alleles of the *Vrn-A1, Vrn-B1* genes, and a dominant allele of the *Vrn-D1* gene reduced the further need for vernalization (Filobok *et al*., 2016).

The detection of a dominant allele of the Vrn-B1 locus emerged in several Polish cultivars of bread wheat, previously declared as winter forms, classifying these cultivars as optional types (Nowak and Kowalczyk, 2010). The *Vrn-A1* and *Vrn-D1* genes appeared on the long arm of chromosomes 5A and 5D, respectively (Snape *et al.*, 2001). The *Vrn–B1* gene location is on the long arm of chromosome 5B (Leonova *et al*., 2003). The *Ppd* genes occurred on the short arm of homologous chromosomes of group 2 (Beales *et al*., 2007). Recessive alleles of *PPd* genes provide the highest photosensitivity to day-length, and slow down the development and timing of the onset of the flowering phase during short days (Muterko *et al*., 2016).

Molecular markers associated with gene loci regulate the type of development that have reached construction and testing related with the efficiency of facultative wheat selection, which can incur significant improvement using DNA markers (Yan *et al*., 2004, 2006; Fu *et al*., 2005; Shcherban *et al*., 2013). Separate studies exist on already developed, varietal material of wheat, aimed at assessing the genetic diversity of the vernalization and photosensitivity genes, with published methodological recommendations (Zlotina *et al.,* 2012). However, these achievements are yet to implement into practical selection.

Thus, in connection with the growing interest in Central and Eastern Europe for the cultivation of facultative wheat in late autumn, genetic studies and field evaluation materialized on four spring cultivars, i.e., *Tubalt* (Netherlands), *Monsun* (Germany), *Ostka Smolicza,* and *Bombona* (Poland). Molecular analysis of the *PPD-D1* gene confirmed the presence of the photoperiod-sensitive allele ppd-D1b in all the tested spring wheat genotypes. The highest level of the NRE *WCS120* gene was evident in the cultivars *Tubalt* and *Bombona*. Based on the field experiments and molecular analysis of the *PPD-D1* gene alleles, the tested strains can be considerably as potential facultative wheat genotypes (Anna *et al*., 2016).

CONCLUSIONS

In the present era, the selection of facultative wheat cultivars is one of the priority areas of agriculture research. By studying the targeted selection of facultative wheat in the world, more than 20 cultivars have succeeded development, which have active uses in production in countries, such as, Russia, Kazakhstan, Kyrgyzstan, Armenia, Turkey, and New Zealand. With the development of biotechnology, more opportunities surface to obtain new types of facultative wheat cultivars meeting the demands of better productivity and grain quality in the modern world.

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