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Review

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Anther culture in rice: from an experimental model to breeding practice

The anther culture method has become an effective tool in modern rice breeding, enabling a significant reduction in the breeding cycle through the rapid production of haploid and doubled haploid plants. Extensive global experience, particularly in major rice-producing countries such as China, Japan, and India, confirms the importance of androgenesis technology for developing new high-yielding and high-quality rice varieties. The efficiency of this method depends on multiple interacting factors, the most critical being genotype. Studies have shown that the japonica subspecies of rice is markedly more responsive and suitable for anther culture, whereas the indica subspecies is typically exhibits low callus induction and regeneration capacity. To overcome these limitations, inter-subspecific hybridization and optimization of culture protocols are commonly employed. This approach has also been successfully implemented in Kazakhstan, where several new rice lines and varieties have been developed. In particular, the cultivar Fatima demonstrates increased productivity (~5.1 t/ha) and valuable agronomic traits and has already been released for cultivation in the country's major rice-growing regions. Moreover, anther culture has enabled Kazakhstani breeders to obtain doubled haploid lines surpassing their parental forms in several agronomic characteristics, such as the glutinous variety Violetta. In conclusion, anther culture in rice holds considerable potential for accelerating the development of homozygous lines and novel genotypes. The integration of this approach with molecular tools such as marker-assisted selection (MAS) and CRISPR/Cas9 genome editing offers new opportunities for targeted gene combination and for expediting the development of improved rice varieties with desired traits.

Keywords: rice, male gametophyte, anther and microspore culture, androgenesis in vitro, biological, chemical, physical factors.

Introduction

One of the most significant areas of haploid plant biotechnology is anther culture in rice (Oryza sativa L.), which enables the production of homozygous lines in a single generation and significantly shortens the breeding cycle [1]. This technology is based on the phenomenon of androgenesis, that is, the reprogramming of microspores from the gametophyte to the sporophyte pathway [2-3]. This in turn leads to the emergence of regenerated haploid plants, which can subsequently be doubled to produce a diploid plant [4]. The anther culture method allows for the production of stable inbred lines without long-term pollination, making it a powerful tool for both applied breeding, which includes accelerated variety development, and for fundamental genetic research, such as QTL analysis, genomic mapping, and transgenesis [5-6]. Haploid rice varieties were first obtained in 1931 by Morinaga and Fukushima by crossing two varieties (Dekiyama ♀ x Bunketu ♂) [7]. In 1933, Nakamura [8] described the haploid rice plant, and the first successful experiments on androgenesis *in vitro* were conducted by Niizeki and Oono in 1968 [9] using anther cultures of six rice varieties. In 1970, Guha and co-authors identified the use of totipotent male cells in gametophytic rice plants [10]. In 1975, as a result of comparative experiments on nitrogen sources, the effective Chu medium for culturing haploids was developed, which subsequently influenced the creation of the now widely used N6 medium [11-12]. Since then, this method has undergone intensive development, and by the 1980s, the first androgenic rice varieties (Huayu I, Huayu II, Xin Xiu, Late Keng 959, Tunghua 1, Tunghua 2, Tunghua 3) were obtained in China [13]. These varieties combined several beneficial properties, such as productivity, stability, and high grain quality. Today, the anther culture method is recognized worldwide as a necessary component of breeding program [14-15].

Despite its widespread use and effectiveness in breeding Japonica rice, it still faces limiting factors associated with Indica rice, including early anther necrosis, poor callus induction and proliferation, low green plant regeneration, and a high level of albinism in regenerated plants [16]. These issues stem from the molecular and physiological characteristics of microspores, which require comprehensive optimization, including selection of donor genotypes, precise selection of nutrient medium composition, cultivation conditions, and stress management [17-18]. Rice cultivation in Kazakhstan is export-oriented, making accelerated breeding and the development of resilient, high-quality rice varieties extremely pressing [19]. This article aims to comprehensively analyze the physical, chemical, and biological factors that influence the success of androgenesis, identify the weak points of the method, and discuss current, modern strategies for integration into molecular and genomic rice breeding in the country.

Experimental

A review of available sources was conducted using the Scopus/Web of Science database for the period 1930–2025. The following keywords were used in the search for literature sources: rice; physical, chemical, and biological factors of androgenesis; methods for rice androgenesis; strategies for integration; molecular and genomic rice breeding.

Review

Factors affecting the efficiency of in vitro androgenesis—biological, chemical, and physical conditions determining the success of anther culture

A review of the literature and practical experiments revealed that the success of rice anther and microspore culture in vitro is determined by the combined effects of three main groups of factors: biological, chemical, and physical. The interaction of these factors determines the ability of microspores to develop sporophytically, forming callus tissue and viable regenerants.

Biological Factors

Biological factors include the genotype, physiological state of the donor plant, and the developmental stage of the male gametophyte [3, 17, 18, 20]. The genotype of the donor plant, in turn, determines the embryogenic potential of rice microspores [21]. Japonica subspecies varieties are generally more responsive to androgenesis than indica varieties. These differences are due to plastid and nuclear genes responsible for chloroplast biogenesis and morphogenesis [21]. According to research results, anthers from fully developed and healthy plants have a higher embryogenesis potential, especially if optimal cultivation conditions were selected. A critical factor influencing the efficiency of *in vitro* androgenesis in anther culture is the quality of donor plants [1, 18, 20, 22]. The process of accelerated dihaploid production directly depends on the health of the plant, its shoots and ears. Two cultivation methods are most frequently used: controlled conditions in a greenhouse or phytotron chamber, or favorable field conditions in a nursery [23]. Based on experimental data, it has been shown that donor plants grown in field conditions outperform those obtained under controlled conditions [24]. Such regenerants develop significantly more shoots and have a developed ear with large anthers and microspores [24-25]. This difference is directly related to the number of viable microspores developing in the anthers and the nutritional status of the anther tissues [26]. Thus, the stage of microspore development is a critical factor that influences the direction of cell differentiation [27]. It has been shown that microspores at the middle or late mononuclear stage, when the cells are still weakly differentiated but still retain totipotency, are most susceptible to androgenesis [3, 27-28]. At the same time, overmature microspores lose their activity in morphogenesis, and, conversely, those that are too young are not yet able to respond to induction signals [1, 3, 18, 20, 22, 26-27].

Chemical Factors

The composition of the nutrient medium plays a central role in the regulation of androgenesis. The most important components are the mineral composition of the medium, particularly nitrogen sources (ammonium and nitrate), trace elements, and the concentration and combination of phytohormones. An optimal balance between these substances has a critical impact on callus induction and the development of regenerated plants. The most widely used basic nutrient media and their modifications include Murashige and Skoog (MS), Gamborga B-5, N6, and others, which demonstrate high efficiency for various rice genotypes [1, 3, 18, 20, 29]. Carbohydrates are used as an energy source and osmotic agent, and the type of source chosen directly influences anther response [28]. Literature data indicate that maltose is more effective in anther culture than sucrose, which can have a toxic effect when broken down into glucose and fructose [27, 30]. In addition, organic additives such as yeast extracts, casein hydrolysate, amino acids (glutamine, proline), and vitamins (thiamine, inositol) affect the acceleration of cellular metabolic activity and morphogenesis [3, 18, 20]. For work with sensitive varieties, as well as to prevent necrosis and browning, antioxidants and phenol adsorbents (ascorbic acid, PVP, $AgNO_3$) are added to the nutrient medium [22, 29]. Agar is mainly used as a gelling agent in solid nutrient media; however, some studies have noted that when agar was replaced with Gelrite, starch increased the efficiency of androgenesis in vitro [27, 31].

Physical factors

Physical conditions significantly influence the effectiveness of androgenesis. Anthers can be cultured on both solid and liquid nutrient media [3, 18, 20]. However, it has been noted that combined and two-phase media promote nutrient diffusion and improve aeration, which directly impacts embryo development [22, 29]. Stress pretreatment is most commonly used in rice anther culture, primarily cold treatment at temperatures ranging from +4 to +10 °C for several days; less commonly, heat treatment at +33-35 °C, as well as a combination of both, is used. Osmotic stress, such as sucrose starvation, radiation, and electrical stimulation, is also introduced [3, 18, 20, 22, 29]. Light and temperature conditions are also important for microspore cultivation, influencing photomorphogenesis and regeneration [32–34]. Therefore, during the initial stages, cultures are incubated in the dark and then transferred to a photoperiod at a temperature of 25–28 °C, which stimulates seedling formation. This range of treatments is necessary to induce the process of microspore reprogramming to sporophytic development [35-36].

In summary, the success of anther culture depends on the careful selection of all the above parameters, taking into account the specific rice genotype. Only a comprehensive approach to the physical, chemical, and biological components will increase the efficiency of androgenesis and guarantee a high regeneration rate of green, viable plants [37–39].

Anther culture specifics in different rice subspecies

The specific subspecies of rice from which the source material belongs is a critical factor influencing the success of androgenesis. Although the japonica and indica subspecies share a common genetic foundation, their distinct responses to anther culture are explained by differences in the physiological and biochemical characteristics of these subspecies. It has been noted that japonica subspecies varieties exhibit stable callus formation and high responsiveness, as well as a high percentage of regenerated plants, making them a model for androgenesis [40-41]. Meanwhile, the indica subspecies exhibits pronounced recalcitrance, i.e., a low capacity for callus formation, weak embryogenic competence, and an extremely high incidence of albino plants. These difficulties are complex in nature and are associated with the expression characteristics of heat shock genes (HSPs), stress response proteins, and antioxidant defense enzymes, which determine the successful development of microspores from the gametophyte to the sporophyte. The indica subspecies is also characterized by high activity of polyphenoloxidases, which affect the browning of calli and anthers themselves, which in turn causes necrosis and the accumulation of phenolic compounds that have a detrimental toxic effect [42]. The main goal of haploid technology was to overcome recalcitrance. It is known from the literature that the most effective intersubspecific hybrids (F_1 indica × japonica), possessing combined embryogenic competence, turned out to be the first generation; the use of stress treatments (short-term cold shock at 8–10 °C, osmotic stress, sucrose starvation), aimed at activating the sporophytic development program; The replacement of sucrose with maltose as a more stable carbon source; and the addition of silver nitrate ($AgNO_3$) to suppress tissue browning [43, 44]. Significant progress has been achieved using various modifications to nutrient media, including enrichment with casein hydrolysate, glutamines, and ammonium and potassium salts. The use of isolated microspore culture has proven to be the most promising, increasing the ability to control the conditions for embryogenesis and eliminating the influence of somatic tissues [45].

Efficiency of the anther culture method in applied rice breeding

Anther culture technology has proven to be an effective tool for enhancing breeding, enabling the production of homozygous rice lines in a single generation and shortening the breeding cycle. Over the past decades, the method has been successfully implemented in practice, as evidenced by the development of new rice varieties worldwide. Back in the 1980s, Chinese scientists developed the “Huayu 15” variety, which yielded 8–11 t/ha. It was created from a haploid F-1 hybrid plant through anther culture followed by double haploidization. This variety demonstrated that anther culture enables heterosis while maintaining stability and uniformity in the offspring. Since then, dozens of highly productive rice varieties have been developed in China through anther culture [41]. These plants are resistant to a range of diseases, are high-yielding, and are characterized by high-quality grain. By 2015, more than 100 rice lines and varieties had been bred in China. Therefore, China is a striking example of the large-scale implementation of androgenic technology in rice breeding. Domestic experience describes the development of the early-ripening rice variety “Fatima”, obtained by breeders at the I. Zhakhaev Kazakh Research Institute of Rice Growing. This variety was obtained through anther culture from the mutant IRRI line (Dihaloid Ko 293), which allowed for the retention of valuable traits in the homozygous state. In state trials, “Fatima” demonstrated a yield increase of 6–10 % compared to the standard in various growing regions. Furthermore, the variety exhibits good resistance to lodging, grain shattering, pests, and diseases. “Fatima” was one of the first Kazakh rice varieties to clearly demonstrate the effectiveness of anther culture for the accelerated development of new competitive varieties [46]. These examples confirm that the inclusion of anther culture in breeding programs significantly accelerates the development of genetically uniform lines and new rice varieties with improved properties [47].

Challenges in Rice Anther Cultivation

Rice anther culture in breeding allows for shorter cycles and increased hybridization efficiency. Furthermore, this method is easily integrated into transgenesis using molecular markers, enabling the development of new varieties with multiple resistances, adapted to various conditions, superior quality, and high yields (Tab. 1). However, the practical use of rice anther culture still faces a number of challenges that limit its full potential.

Table 1

Rice varieties obtained from anther culture

Variety	Characteristics	Country	Links
Danfeng 1	High grain quality, high yield	China	[48]
Zhonghua 8, Zhonghua 9	Blast resistance	China	[49]
Zhonghua 10	High grain quality, salt tolerance	China	[50]
1647S	High yield	China	[51]
Huageng 45	Salt tolerance, lodging resistance, fire blight resistance, moderate resistance to anthracnose, cercospora leaf spot, and false smut	China	[52]
Hejiang 21, Longgeng 1, Longgeng 3, Longgeng 4, Longgeng 7, Longgeng 8	Blast resistance, high grain quality, high yield	China	[53]
Jiudao 26	Moderately resistant to leaf scab, moderately susceptible to panicle scab, high grain quality	China	[54]
Zhonghua 15	Resistance to fire blight and blast, high yield	China	[55]
Huageng 15	Salt tolerance	China	[56]
Zhonghua 14, Zhonghua 16	Salt tolerance, lodging resistance, drought tolerance	China	[57, 58]
Longgeng 10, Longgeng 12	Blast resistance, high quality	China	[59, 60]
Huayu 13	Resistance to blast, leaf rot, and false smut, high grain quality, good flavor, high yield	China	[61]
Huayu 15	Lodging and disease resistance, good grain quality	China	[62]
HD27	High grain quality, resistance to diseases, early flowering	China	[63]
Chongshang 2022	Scab and lodging resistance, good grain quality	China	[64]
Shuhui 162	Scab resistance, high grain quality	China	[65]
Hua 1B	Good crossing characteristics, high combining ability	China	[66]
Hua 2B	High grain quality	China	[67]
Hua 03	High protein content (13.7 %)	China	[68]
Chuanhui 907		China	[69]
Chuanhui 1618	High grain quality, blast resistance	China	[70]
Miai 64S	Large panicle, high grain quality, blast resistance	China	[71]
1103S, 8906S, 8902S	High yield	China	[72]
Liangyou 1178	Stable sterility, practical significance for the breeding process	China	[72]

Continuation of Table 1

Variety	Characteristics	Country	Links
HS-1, HS-2, HS-3	High yield, high grain quality, multifactorial resistance	China	[73]
Hua 1A	Good crossing characteristics, high combining ability	China	[74]
1286S, 6442S	Good crossing characteristics, high combining ability	China	[75]
Jinshan S-1	High yield	China	[76]
Huaxiang 7	Stable sterility, practical significance for the breeding process	China	[77]
Xiang 125S	High yield, moderate blast resistance	China	[78]
Hua 2A	High grain quality	China	[79]
V25S	Stable sterility, practical significance for the breeding process	China	[80]
EH1S	High seed set percentage Crossbreeding, high grain quality	China	[81]
Guan 18, Gan Xhao Xian 11	High seed set rate in crossbreeding, blast resistance	China	[82]
Huayu 15	Early maturity, disease resistance	China	[62]
Huayu I, Huayu II, Xin Xiu, Late Keng 959, Tunghua 1, Tunghua 2, Tunghua 3, Tanghuo 2, Huajian 7902, Zhonghua 9	Resistance to lodging and diseases, good grain quality	China	[68]
Milyang 90	High yield, high grain quality, resistance to blast and bacterial blight	China	[83]
CR Dhan 10 (CRAC2221–43), Satyakrishna	Good grain quality, resistance to brown leafhopper and stripe virus	India	[84]
CR Dhan 801 (CRAC2224–1041, IET18720), Phalguni	Resistance to leaf rot and stem borer	India	[85]
Janka	Resistance to blast and gall midge, moderate resistance to stripe virus, yellow stem rust, and brown spot	India	[86]
Abel	Drought resistance, good grain quality	India	[86]
Parag 401	Cold tolerance	India	[87]
Risabell	High grain quality, resistance to chlorosis caused by iron deficiency	India	[86]
Hwacheongbyeo, Joryeongbyeo, Hwajinbyeo	High grain quality, good taste	South Korea	[88]
PSBRc 50 Bycol (IR 51500-AC11-1)	Resistance to brown leafhopper, stripe virus, blast, and bacterial blight Scald	South Korea	[89]
Privolny-4	Salt-tolerant	Russia	[41]
Sonnet	Blast-resistant, high yield, does not require high fertilizer doses	Russia	[41]
Bicol (IR51500AC11–1)	Can be grown under various irrigation regimes, does not shatter when overripe, good flavor	Philippines	[90]
AC-1	Salt-tolerant	Bangladesh	[91]
Joiku 394, Hirohikari, AC. No.1, Hirohonami, Kibinohana	Salt-tolerant	Japan	[92]
Dama	Cold-tolerant	Hungary	[93]
Fatima	High yield, blast-resistant, good flavor	Kazakhstan (Institute of Plant Biology and Biotechnology)	[94]

The key issue in rice anther culture breeding is genotype, as it largely determines the effectiveness of the method. Current breeding programs face numerous challenges, including lengthy stages, a high workload, low callus formation rates, low green shoot regeneration rates, and low androgenesis efficiency in rice of the indica subspecies. To mitigate genotype limitations, previous studies have suggested selecting parent materials with high anther culture efficiency or using indica-japonica hybrid progeny with a higher proportion of japonica ancestry to exploit heterosis and improve anther culture efficiency. Furthermore, identifying genes that influence anther culture efficiency and using transgenesis with molecular markers can alleviate genotype limitations.

The occurrence of albino plants, as well as browning of callus and anthers, negatively impacts androgenesis efficiency. Albinism is a recessive trait controlled by a group of loci of abnormal gene expression or mutations; the absence of chloroplasts is influenced by both genes and environmental factors [95]. Browning occurs upon activation of polyphenoloxidases produced in tissues and leading to inactivation of other enzymes, which inhibits growth [96]. Any anther is susceptible to browning, regardless of age, and high concentrations of inorganic salts and sugars in the nutrient medium can accelerate this process. An effective strategy for preventing these two phenomena may be the selection of young spikelets whose anthers are still mononuclear, regulation of environmental parameters (light, temperature), and the use of various antioxidants (activated carbon, PVP, vitamin C, and $Na_2S_2O_3$) [97]. In another case, it was shown that insertion of a transposon into the BOC1 gene promoter reduces callus browning in culture [98]. Literature data have shown that reducing the manganese content and the concentration of inorganic salts in the callus induction medium, as well as optimizing the concentration of hormones (e.g., KT or 2,4-D) can reduce the formation of albino plants and simultaneously increase the callusogenesis rates [99].

QTLs associated with antheric cultivability in rice

The ability of rice microspores to develop in culture is a complex quantitative trait controlled by a large number of genes. Furthermore, genotypic differences depend on the rice subspecies. Literature data have shown that QTL mapping methods have yielded a number of loci that influence key stages of androgenesis [100]. Experiments with a DH population (double haploids) from a cross between the indica × japonica subspecies revealed QTLs associated with callus formation frequency located on chromosomes 6, 7, 8, 10, and 12, as well as those for the ability to regenerate green plants on chromosomes 1 and 9, respectively. A QTL responsible for the formation of albinos was also found on chromosome 9. In another study, a QTL associated with green plant regeneration was mapped on chromosome 10 and used to select plants with enhanced regeneration capacity in the Milyan 23 × Gihobyeo rice population [101]. As a result, the marker associated with this locus was integrated into the MAS program to obtain a new rice line with enhanced regeneration capacity, saving time and resources for obtaining DH forms. Despite the difficulties of phenotyping, which limit the number of QTL in androgenesis, the use of modern methods, in particular Segregation Distortion Analysis, provides new opportunities for mapping the corresponding loci. Using this method, five loci were identified: SDL1.1, SDL1.2, SDL2, SDL5, SDL7 (2023), the alleles of which were successfully transmitted to DH progeny with increased frequency, indicating successful microspore development *in vitro* [102].

Prospects for the development of anther culture—new technologies and integrated approaches

Rice anther culture is a highly promising method with enormous potential for accelerating rice breeding. Isolated microspores are easily cryopreserved, which is useful for long-term storage of haploid material. However, anther culture remains a time-consuming and labor-intensive method, which poses a significant challenge to scalability. Future advances anticipate the introduction of high-throughput automated systems. Advanced molecular breeding approaches are actively integrating anther culture with high-precision genetic tools, such as genome editing technologies (CRISPR/Cas9) and marker-assisted selection (MAS) [103]. Combining androgenesis with MAS offers expanded opportunities for breeding new varieties and increases the accuracy of early-stage selection. Selecting hybrids using molecular markers followed by fixation of the desired genotype using anther culture creates conditions for the rapid production of homozygous lines containing desired alleles for quality, resistance, or productivity. This approach has already proven successful in a number of breeding programs, for example, in the development of early-ripening, high-yielding Chinese varieties. The effectiveness of the MAS method is also reflected in the screening of DH lines, allowing for the rapid identification of promising forms, bypassing years of field trials. In a more technologically advanced perspective, rice anther culture can be combined with genome editing methods. This can be achieved by editing parental forms or by directly delivering CRISPR/Cas9 complexes to embryogenic calli or microspores. This makes it possible to introduce the necessary point mutations and immediately obtain homozygous plants without lengthy selection. Furthermore, editing genes that limit the efficiency of androgenesis itself, particularly those responsible for albinism, opens a new avenue for significantly increasing the effectiveness of the technology itself. Thus, introducing MAS and CRISPR/Cas9 tools into anther culture allows for the dramatic acceleration of the selection process, improvement of the source material, and the capture of valuable traits [104, 105]. All of this makes androgenesis a crucial element of the modern biotechnological platform in rice cultivation.

Conclusion

Anther culture is increasingly integrated into modern breeding strategies as a tool for “accelerated breeding”, revolutionizing rice breeding by significantly accelerating the development of new lines and varieties. The use of anther culture allows for the reduction of the breeding cycle for a new variety from 6–8 generations to 2-3, which is particularly important for strategically important crops such as rice. Anther culture makes it possible to quickly respond to production needs, from improving yield and grain quality to introducing disease resistance genes. Combining this method with marker-assisted selection and genome editing (MAS, CRISPR/Cas9) enables the targeted production of homozygous lines with specific sets of valuable traits in a single generation. In China, over 200 commercial rice varieties have been developed through anther culture, many of which have occupied significant acreage and contribute to food security. In Vietnam, India, Bangladesh, and other Asian countries, haploid technologies are also used for the accelerated improvement of local varieties (improving quality, disease resistance, and producing lines for hybrid breeding). Kazakhstan’s experience with the Fatima variety demonstrates the method’s effectiveness even in the harsh continental climate of Central Asia. Thus, the method serves as a cornerstone of modern breeding programs, complementing traditional hybridization and integrating with molecular and genomic technologies.

The responsiveness of anthers and microspores cultured in vitro is influenced by many interacting factors: growing conditions of the donor plants, genotype, physiological state of the donor plant, stage of microspore development, anther pretreatment, and the composition of the nutrient medium. To improve the efficiency of producing haploids and dihaploids, it is necessary to conduct a comprehensive study to evaluate the structural features and physiological mechanisms of the anther cell reprogramming process and their responsiveness to cultivation conditions. The development and use of new rice varieties that are resistant to pests, diseases, and drought, as well as tolerant of saline-alkaline environments, high-yielding, and of superior quality, can be facilitated by integrating anther culture with other technologies, such as transgenic technology, molecular marker-assisted selection, and CRISPR/Cas9 gene editing. Standardizing and simplifying anther culture protocols to minimize the impact of experimental operations, along with improving the anther culture system in rice, will facilitate the development and use of new rice varieties and enrich rice germplasm resources in Kazakhstan. Anther culture in rice has evolved from basic experimental protocols to high-tech breeding systems. Historical successes and ongoing challenges (recalcitrance, albinism, variability) are supported by modern technological solutions, making this method an effective tool for modern rice improvement programs.

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Conflict of interest

The authors declare no conflict of interest.

Author contribution

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript: **Usenbekov B.N.** — conceptualization, data analysis, investigation; **Mukhambetzhanov S.K., Kurbangaliyeva T.A., Amirova A.K.** — data analysis, writing draft; **Sartbayeva I.A., Kirshibaev E.A., Gabdullina Ye.Zh., Yerezhepov D.A., Yerezhepov A.E.** — data curation, data collection, draft writing.

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Күріш дақылының тозаңдануы: эксперименттік модельден селекциялық тәжірибеге дейін

Дақылдың тозаңдану әдістері гаплоидтар мен дигаплоидтарды жедел алу есебінен селекциялық циклді едәуір қысқартуға мүмкіндік беретін заманауи күріш селекциясының тиімді құралы. Қытай, Жапония, Индия және басқа да елдерде жиналған әлемдік үлкен тәжірибе жоғары өнімді және сапалы жаңа күріш сорттарын шығаруда андрогенез технологиясының өте бағалы екендігін дәлелдейді. Бұл әдістің тиімділігі бірқатар факторларға байланысты, олардың негізгісі — генотип. Тәжірибеде *japonica* түртармағының күріштері каллусогенез және регенерацияға жоғары қабілеттілігімен ерекшеленетіндігі, ал *indica* түртармағы күріштері үшін бұл қасиет төмен болатындығы көрсетілген. Бұндай қиындықтарды шешу үшін будандастыру және протоколда оңтайландырудың әртүрлі әдістері кеңінен қолданылады. Бұл әдіс бірнеше жаңа күріш қатарлары мен сорттары шығарылған Қазақстанда да тиімді болды. Атап айтқанда, өнімділігі жоғары (~5,1 т/га) және құнды, ауылшаруашылық қасиеттері бар «Фатима» сорты еліміздің негізгі күріш өсіретін аймақтарына аудандастырылған. Дақылды тозаңдану арқылы өсіру әдісі Қазақстандағы селекционерлерге бірқатар агрономиялық қасиеттері бойынша бастапқыдан асып түсетін дигаплоидты қатарларды жасауға мүмкіндік берді (мысалы, глютинозды «Виолетта» сортының қатарлары). Күріш дақылының тозаңдануында жаңа генотиптерді және гомозиготалы қатарларды жылдам алуда потенциалы жоғары. Бұл құралды молекулалық тәсілдермен — маркер-ассосацияланған селекциямен (MAS) және CRISPR/Cas9 геномды редакциялау технологияларымен интеграциялауға болады, бұл нақты гендерді сәйкестендіруге және сапалы қасиеттері бар жаңа сорттарды шығару процесін едәуір жеделдетуге мүмкіндік береді.

Кілт сөздер: күріштің тозаңдануы, *in vitro* андрогенез, гаплоидтар, дигаплоидтар, *Oryza sativa* (*indica, japonica*), күріш селекциясы, маркерлік селекция (MAS), CRISPR/Cas9

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Культура пыльников у риса: от экспериментальной модели к селекционной практике

Метод культуры пыльников представляет собой эффективный инструмент современной селекции риса, позволяющий значительно сократить селекционный цикл за счет быстрого получения гаплоидов и дигаплоидов. Огромный мировой опыт, накопленный в Китае, Японии, Индии и других странах, подтверждает большую ценность технологии андрогенеза в выведении новых высокопродуктивных и качественных сортов риса. Эффективность данного метода зависит от комплекса факторов, ключевым из которых является генотип. Показано, что подвид риса japonica является значительно более отзывчивым и удобным на практике, тогда как для подвида indica характерна низкая способность к каллусогенезу и регенерации. Для преодоления этих трудностей широко применяется гибридизация и различные способы оптимизации протоколов. Данный метод также зарекомендовал себя и в Казахстане, где получен ряд новых линий и сортов риса. В частности, сорт «Фатима» отличается повышенной урожайностью (~5,1 т/га) и несет ценные хозяйственные признаки, и уже районирован в основных рисосеющих регионах страны. Метод культуры пыльников позволил селекционерам Казахстана вывести дигаплоидные линии, превосходящие исходные по ряду агрономических качеств (например, линии глютинозного сорта «Виолетта»). Обобщая, культура пыльников риса имеет высокий потенциал в ускоренном получении гомозиготных линий и получении новых генотипов. Данный инструмент можно интегрировать с молекулярными подходами — маркер-ассоциированной селекцией (MAS) и технологиями редактирования генома CRISPR/Cas9, что позволит сочетать конкретные гены и значительно ускорить процесс выведения новых сортов с интересующими характеристиками.

Ключевые слова: культура пыльников, андрогенез *in vitro*, гаплоиды, дигаплоиды, *Oryza sativa* (indica, japonica), селекция риса, маркерная селекция (MAS), CRISPR/Cas9

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