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OBJECTIVES OF GUAR BREEDING IN THE RUSSIAN FEDERATION IN CONNECTION WITH THE PROSPECTS OF DOMESTIC GUAR GUM PRODUCTION

(review)

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Abstract

Guar (*Cyamopsis tetragonoloba* (L.) Taub is a source of guar gum extracted from the endosperm of this annual legume plant (D. Mugdil et al., 2014; R. Pathak et al., 2015). Guar gum has a wide range of applications as gel-forming agent in gas/oil industry and as emulsifier and thickener of substances in food, cosmetic, textile and paper industries (R.J. Chudzikowski et al., 1971; N.Thombare et al., 2016; A.M.A. Hasan et al., 2018). Guar has moderate drought-resistance, it is tolerant to salinized soils and has low demands to soil fertility (D.J. Undersander et al., 1991; R.K. Bhatt et al., 2017). Domestication of guar took place in India and Pakistan where the plant was used as a forage crop (N. Thombare et al., 2016). These countries are the main manufacturers and exporters of Guar gum in the world market today. Guar was introduced into Russian Federation in terms of import submission. Production batches of conditioned seeds were obtained in some regions of South Federal Part and Lower Volga adjacent area last years. Experimental batches of gum extracted from native seeds have demonstrated that guar gum fits the quality standards (I.V. Kruchina-Bogdanov et al., 2019) and in the nearest future guar gum would be produced in Russia. There is a high demand in industrialized-type guar cultivars, well adopted to diverse local conditions in the Russian Federation. Guar was introduced into culture in the Russian Federation, 4 cultivars among 10 registered in the State Register of Breeding achievements were originated by VIR (Vavilov Institute of Plant Genetic Resources). Gum production depends upon guar yield productivity so the problem of high yield is urgent (A.K. Jukanti et al., 2019). However, in the Russian Federation, the most limiting factor for guar production is high temperature demand of the crop (D.V. Lebed et al., 2017), so precocity becomes a priority feature, which, in turn, is associated with the sensitivity of the plant to the photoperiod. Therefore, it is necessary to search in the gene pool for forms with reduced sensitivity to photoperiod, capable for forming full-fledged seeds in a relatively short summer (S.B. Teplyakova et al., 2019). Being introduced to northern altitudes, guar plants may form blackened seeds in pods in conditions of prolonged vegetative period combined with low night temperatures and extra moisture (T. Hymovitz et al., 1963; D.V. Lebed et al., 2018). Due to this fact it is important to use most early guar varieties in Russia. The question arises about the optimal plant architectonics for the conditions of the Russian Federation, contributing to the formation of high productive agrocenosis (M.I. Voloshin et al., 2019). One-stem and few-branched guar plants are recommended as most early and better adopted to mechanized harvesting, such type of plants fit the model of industrial variety (F. Gresta F. et al., 2018; C.M.G. Reis et al., 2021). Plants with determinated type of growth are also early maturing (E.A. Dzyubenko et al., 2017). Guar, like most annual crops, is self-pollinated (R.E. Stafford et al., 1975), its hybridization is a complicated procedure, and the rate of successful crosses is very low (R.E. Stafford et al., 1980). Main breeding method in guar is selection of outstanding genotypes (A.K. Jukanti et al., 2019). The most effective selection index for breeding for high yield in guar is the number of pods per plant (F. Gresta et al., 2013). The diversity of plant genetic resources and the evolving genomic resources allow the use of traditional, biotechnological and molecular approaches in guar breeding (S. Kumar et al., 2017). Some types of molecular markers are identified but not too much compared to other legume cultures (W. Ravelombola et al., 2021). It is also necessary to be ready to resist to the effects of biotic stressors — diseases and pests, it is urgent to create resistant varieties with a broad genetic basis (E.E. Radchenko et al., 2018). The whole range of these issues is outlined in this review as the objectives that domestic guar breeders face when creating gum-forming varieties. Prospects of marker-assisted selection and genomic breeding are under discussion (S. Kumar et al., 2020; E. Gigoreva et al., 2021; S. Pareek et al., 2022). The created domestic varieties of guar were obtained by traditional breeding, but the active development of genomic, metabolomic and transcriptomic resources of the species allow us to hope for a quick practical application of breakthrough methods of crop breeding that will increase crop yield and adaptation in the conditions of the Russian Federation.

Keywords: guar, guar gum, introduction, breeding, seed yield, early maturation

Guar *Cyamopsis tetragonoloba* (L.) Taub is an annual leguminous crop that in recent decades has become a world's most sought after sources of galactomannan, a seed polysaccharide that, after extraction and processing, is used as guar gum (guaran). In terms of the scale of application in various industries, plant galactomannans and their derivatives come after cellulose and starch. These polysaccharides, due to the unique properties of their aqueous solutions and lack of toxicity, are used as food additives, stabilizers, flocculants, thickeners and gelling agents in binary mixtures [1].

Guar gum is the most sought after galactomannan in the world due to its safety and non-toxicity, the extraction from renewable natural resources, and is easily available in large quantities. It is widely used as a natural thickener, stabilizer and sealant in the paper, textile, pharmaceutical, food and cosmetics industries, but is especially in demand in the oil and gas industry [2-6]. Domestication of guar occurred in South Asia, and for a long time the main producers of the crop, primarily as a forage plant, were India and Pakistan. These countries remain the leaders in guar production today, having the status of leading exporters of seeds and the gum obtained from them. To date, the production range of guar has expanded, but is limited mainly to the tropical regions of the USA, Australia, Brazil and some African countries. The annual production of guar seeds worldwide is approximately 3.4 million tons [7]. The Russian Federation, along with Germany, the Netherlands, Italy, France, Spain and the UK, is the largest importer of guar gum in Europe [8]. Dependence on imported guarana prompted Russian scientists and farmers to take active steps to introduce the crop into Russia. In the Krasnodar Territory, Rostov Provunce and Crimea, private farms and breeders have appeared, trying to implement guar production and selection. This served as an impetus for entrying new accessions into the VIR collection (Vavilov All-Russian Institute of Plant Genetic) and initiating crop study by Russian scientists. There are reports on various aspects of the guar biology in different locations [9-11], on the traits intraspecific variability when growing guar in the Russian Federation [12], on guar pathogens and the susceptibility of the guar gene pool to these pathogens [13, 14].

For any introduced species, when cultivated in atypical conditions, problems arise in selecting agrotechnology, combating diseases and pests, and improving existing varieties. High seed productivity and quality are the key issues in gum production. Varieties introduced into the Russian Federation from tropical and subtropical regions, even high-productive, may not correspond to local environmental and climatic conditions, the length of the photoperiod. In addition, they may be susceptible to local biotic and abiotic stressors. It is necessary to create domestic varieties of guar, adapted to the specific conditions of the regions.

This article presents an analysis of the results of guar cultivation in the Russian Federation, considers the limiting factors for crop production and outlines the range of tasks facing guar breeders when creating domestic varieties that produce guar gum.

Guar gum: chemical composition and properties. The main component of guar gum is the polysaccharide galactomannan, consisting of D-mannose (Man) and D-galactose (Gal). The chemistry of galactomannan involves the presence of multiple hydroxyl groups, which allow it to combine with other polymers to create new chemically modified compounds with desirable properties that are less expensive, biodegradable, and environmentally friendly [15].

Highly purified guar gum is used in the food industry, while lower quality guarana has many other uses, including as a drilling fluid additive. When used during oil drilling, guar gum prevents water loss from viscous drilling fluid and suspends bentonite clay. Guarana is less expensive than most other drilling fluid thickeners. Of particular importance is that the rheological properties, solution viscosity, and emulsification tendency of natural and chemically modified galactomannans can be altered through interaction with other monomers or polymers of the carbohydrate base [16].

Galactomannans are localized in the cell membranes of endosperm tissue and serve as an energy reserve and regulator of the water balance of the seed during germination. In a number of leguminous plants (e.g., peas, beans), the endosperm is absent, in others it constitutes a small percentage of the seed mass, 14% in fenugreek (*Trigonella foenum-graecum* L.), no more than 6% in alfalfa (*Medicago sativa* L.) [17]. In the guar seed, the endosperm is large, spherical and accounts for 38-45% of its mass [18]. According to various sources, the percentage of structural components of the seed and the biochemical composition of the guar endosperm may vary somewhat (Table 1).

1. Quantitative ratio of structural components of guar *Cyamopsis tetragonoloba* (L.) Taub seed and the endosperm biochemical composition

Component	Percentage
Structural components of a seed [16, 19, 20]	
Testa	14-16
Germ	45
Endosperm	38-45
Biochemical composition of endosperm [18]	
Galactomannan	75-85
Protein	5-6
Ash	0.5-1
Cellulose	2-3
Fat	0.5-0.9
Moisture	8-14

The Man/Gal ratio affects the viscosity of guar gum. This value is species-specific and determines various industrial use of seed galactomannans. Like all biochemical indicators, the galactomannan content (percentage of the dry weight of the seed) depends on the growing conditions and, according to different reports, varies significantly, e.g., within 15.9-31.8% [21], 21.8-34.4% [22], 28.5-32.9% [23], 35.0% [5], 16.8-36.7% [24].

The guar is on average 67-73% mannose and 27-33% galactose, respectively, that is, 2:1 [18]. In other legumes which serve as the main sources of gum the ratio of these components was ~ 1.1:1 in *Trigonella foenum-graecum* L. [25], ~ 3:1 in *Caesalpinia spinosa* (Molina) Kuntze [26], and ~ 4:1 in *Ceratonia siliqua* L. [27]. These differences determine the use of the gum as various additives in the food industry and gelling additives in cosmetics. Galactomannans with Man/Gal proportions of 1.15-2.30 have been identified in the seeds of many wild legume species of the domestic flora [28].

The gum is obtained mainly from crushed endosperm after removing the seed coat [19]. During processing, guar grains are split into two halves of galactomannan-containing endosperm (the so-called split) using special mechanisms, and the embryo and seed coat, which contain protein, are then used in animal feeding [29].

Experience of introduction and production of guar in the Russian Federation. Guar has moderate drought resistance, is tolerant of soil salinity and is undemanding to soil fertility. This plant is 57-110 cm high, blooming mainly with white-pink flowers collected in erect racemes (Fig. 1, a). Mature beans 6-8 cm long contain from 5 to 12 seeds, varying in size between genotypes, the weight of one seed is from 11 to 51 mg [30]. The beans are collected in dense clusters (see Fig. 1, b), due to which the English name of the plant sounds like cluster bean. Guar seeds contain 27-37% protein, concentrated mainly in the germ and seed coat [31]. The color of the seeds varies from dull white to pink, light gray or black, but is predominantly beige (see Fig. 1, c). It should be noted that guar is an excellent soil-improving crop and fits well into crop rotation with wheat, cotton, grain sorghum, and vegetables [32, 33].

Fig. 1. Inflorescences (a)**, beans** (b) **and seeds** (c) **of the guar** ***Cyamopsis tetragonoloba*** **(L.) Taub from the VIR collection** (FRC All-Russian Institute of Plant Genetic Resources named after N.I. Vavilov, St. Petersburg) (photo by E.A. Dzyubenko).

In the Russian Federation, the main limiting factor for guar is heat supply. The sum of effective air temperatures above 10 °C during the growing season should be at least 3400-3500 °C. In terms of summer air temperatures and other climatic indicators, the agricultural regions of the North Caucasus and Crimea are inferior to India, but are close to the United States, where guar is successfully grown in the southern states. The optimal time for sowing guar is when the temperature of the topsoil passes through 20 °C. In this case, 350-500 mm of precipitation during the growing season is sufficient. Consequently, the flat part of the Stavropol and Krasnodar Territories is sufficiently provided with natural moisture to grow guar; in Crimea and the Rostov region it is advisable to carry out additional irrigation [34, 35]. It should be noted that in India, where guar for grain is cultivated mainly on non-irrigated lands in the north-west of the country, in the Thar Desert, varieties intended for food consumption as a vegetable crop are grown in the southern states only under irrigation [36].

The first guar crops in the Krasnodar Territory and Rostov Region appeared in 2011-2014. The maximum seed yield reached 24 c/ha. Physiological maturity of seeds occurred 100-130 days after germination [9, 34]. The dates of timely sowing and harvesting turned out to be critical for the successfu guar l cultivation.

To search for samples adapted to the conditions of the Russian Federation at the Vavilov Research Institute of Plant Genetic Resources for a number of years carried out ecological and geographical testing of guar samples in four geographical points where experimental stations are located: Krasnodar Territory (Krymsk and the village of Gulkevichi) and the Lower Volga region (Volgograd and Astrakhan) [11]. Gum yield and viscosity of samples grown in these regions were assessed. It has been proven that the yield of gum from guar seeds is determined not only by genetic factors, but is also influenced by external conditions.The quality of gum produced from domestic seeds meets the necessary requirements [11, 29].

As the genotypes most adapted to the conditions of the Russian Federation were identified, the breeding domestic guar varieties first started by M.I. Voloshin and Z.S. Vinogradov in 2011-2014, then revived. VIR developed a methodology for assessing guar varieties for distinctiveness, uniformity and stability for the State Commission of the Russian Federation for Variety Testing [37]. In 2018-2019, the State Register of Breeding Achievements was replenished with varieties of domestic selection, including those created by VIR employees, e.g., Vavilovsky 130, VIR 1, Kaspiets, Nakhodka [38]. This is a significant contribution to the country's crop production, considering that there are only 10 zoned varieties in the State Register of Breeding Achievements of the Russian Federation (Table 2).

2. Characteristics of guar *Cyamopsis tetragonoloba* (L.) Taub varieties from the State Register of Breeding Achievements approved for use

Variety	1	2	3	4	5	6	7
Judd	12.5	–	120	–	Нет	2014	West Texas Group
Vavilovsky 130	28.5	32.0	120	Branched	Yes	2018	Vavilov VIR
VIR 1	29.0	41.0	109	Single-stem	Yes	2019	Vavilov VIR
Nakhodka	27.0	–	115	Few-branched	Yes	2019	Vavilov VIR
Kaspiec	27.0	37.1	110	Branched	No	2019	Vavilov VIR
Kubansky	26.0	32.0	120	Branched	Yes	2018	LLC Agroalliance, LLC Nika-Petrotek
Kuban yubileinyi	25.5	45.0	120	Branched	Yes	2018	LLC Agroalliance, LLC Nika-Petrotek
Sinus	28.5	33.8	115	Branched	Yes	2018	Private person
Vector	23.5	32.7	120	Single-stem	Yes	2018	Private person
Pobeda	25.5	40.4	102	Single-stem	No	2020	Private person

Note. 1 — declared seed yield, c/ha; 2 — declared gum content, %; 3 — growing season, days; 4 — type of branching; 5 — pubescence; 6 — year of registration; 7 — originator. Dashes mean no data.

Breeding improvement of a crop should be facilitated by significant polymorphism of traits characteristic of the species. Intervarietal differences in the duration of the growing season, plant height, their pubescence, number and shape of leaves, branches, beans in a cluster, brushes and beans on a plant, dry biomass and seed weight, shape and size of seeds, root length, bean size have been repeatedly noted [12 , 22, 33, 39, 41].

It should be noted that the increased demand for guar in recent years has led to its introduction into a number of countries, e.g., in Italy, Spain, Portugal, China, where intensive study of the culture began.

Guar breeding methodoloy. Like many annual legumes, guar is a self-pollinator; the percentage of natural cross-pollination is insignificant, from 0.3 to 4.4%. Under uncontrolled conditions, the maximum cross-pollination reached 9%, which can be neglected when maintaining the genetic integrity of breeding lines and varieties [42].

Similar to some legumes (soybeans, beans, peanuts, etc.), guar is characterized by bud autogamy, i.e., self-pollination in a closed flower. The guar flower is delicate, with a small stigma, and a tight stamen-pistillate column [43], so the guar hybridization technique is very complex; the proportion of successful crosses with castration is about 4% [44]. An original method of in vivo hybridization of guar was developed - using manipulations with the pistil of a flower, when pollen grains were introduced directly into the tissue of the lower part of the style or ovary through microholes made. The method was developed to produce an interspecific hybrid of *C. tetragonoloba* × *C. serrata* in an attempt to transfer early maturation genes from a wild relative to a cultivated one. One interspecific hybrid plant was obtained. The hybridization method also turned out to be effective for intraspecific hybridization of guar plants, but apparently is not widely practiced [45].

Chemical and physical mutagenesis of guar was used to expand the genetic basis of the crop but no new economically useful traits were obtained [46].

Due to difficulties with hybridization, the main method of guar breeding at present is individual selection of valuable genotypes [43].

Guar genomics and transcriptomics research began only in the 21st century. The size of the guar genome has so far been determined by the amount of DNA, and information is contradictory. Several types of molecular markers have been identified in guar. These are RAPD (random amplified polymorphic DNA), AFLP (amplified fragment length polymorphism), SSR (simple sequence repeats), SNP (single-nucleotide polymorphism) [7], and SCAR (sequence characterized amplified region) [47] markers. Using AFLP markers, a number of agronomically valuable traits were studied, namely, the number of seeds per bean and beans per plant, growth pattern [48]. SSR was used to study genetic diversity [49]. SNPs were identified that can be effective in relation to the number of ripened beans per plant as a trait that determines high guar seed productivity [50]. However, the the number of guar genome markers obtained is still much less than those for other legumes with sequenced genomes, and is not yet sufficient for next-generation breeding programs.

Recent transcriptome sequencing has identified genes involved in biological processes, molecular functions, galactomannan biosynthesis, cellular functions, and stress tolerance pathways [51]. The development of molecular breeding methods, understanding of metabolic pathways, and further marker-mediated selection of guar now rely on next-generation sequencing platforms [47, 52].

The process of galactomannan synthesis in developing guar seeds was also studied using RNA sequencing. To identify genes involved in synthesis, RNA was extracted separately from the embryo and endosperm of the seed 30 and 40 days after flowering. As a result of transcriptomic sequencing of guar endosperm RNA on days 30 and 40, 2535 and 2724 genes with specific expression in the endosperm were identified. Of these, one mannan synthetase gene (Unigene5327), three galactosyltransferase genes (Unigene7196, Unigene23466, Unigene8081) (UniGene database, NCBI), as well as four genes that may be involved in the synthesis of guar galactomannan, were identified based on the degree of expression. According to the authors, this information will be useful for genome editing of crops [53].

Priority traits for improving guar culture in the Russian Federation. In the guar gene pool, like many leguminous crops, there is differentiation into fodder, grain and vegetable varieties. The source of guar gum is grain varieties. It can be noted that in India, the largest exporter of guar gum to the world market, until recently universal grain-feed varieties were cultivated for grain, but in recent decades, targeted selection has been carried out for seed productivity and gum yield [12].

It has been shown that, regardless of the amount of galactomannan in seeds of different genotypes, seed yield is much more influences the yield from the sown area: with an increase in seed yield, the yield of protein and galactomannan per hectare also increases, while an increase in only the content of galactomannan in the seed does not lead to a general increase in the yield of galactomannan [54]. The key property that determines the quantitative yield of galactomannan from a plant is the number of beans per plant [54, 55]. Therefore, the search in the gene pool for genotypes with the maximum yield of gum from the seed is an optional stage in the selection of source material for breeding. Meanwhile, more and more researchers are coming to recognize the number of beans per plant as the most effective breeding criterion by which selection should be made [54-57]. For the Russian Federation, this criterion should be adjusted and take into account the number of ripened beans on the plant, since unripe green beans do not contribute to the harvest.

With the introduction of guar into countries of temperate latitudes, selection for early ripening becomes relevant, since the growing season of the crop in tropical and subtropical conditions is too extended. A comparative study of the duration of the growing season in 68 guar genotypes of different geographical origins in the conditions of Southern Italy showed that this trait varied from 155-163 days in the earliest ripening varieties, to 175-184 days in the latest ripening ones. Under these conditions, guar plants ended their growing season from mid-October to early November, exposed to autumn rains, which negatively affected the quality of the crop [56]. Guar has an indeterminate growth pattern, and the plants continue to flower and set pods until a critical drop in temperature or senescence [48]. Flowers and green beans formed on second-order shoots of branched guar plants significantly complicate the harvesting of ripened beans.

All Russian varieties require a growing season of more than 100 days to ripen seeds. Therefore, early ripening becomes a key trait for relatively northern regions, more important than the selection of highly productive varieties, since physiologically ripe seeds are used to extract gum.

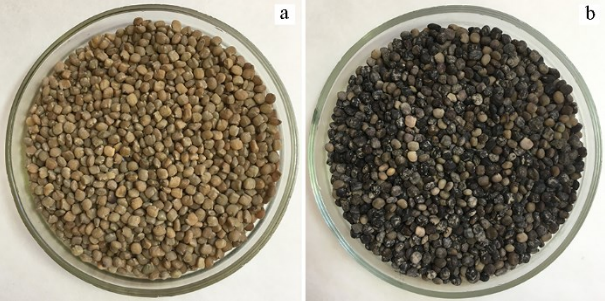

Fig. 2. Guar *Cyamopsis tetragonoloba* (L.) Taub variety Kuban seeds depending on sowing dates: a — normal seed color at optimal sowing time and timely harvesting, b — immature seeds with blackened seed coat as a result of late sowing (Kuban experimental station VIR, 2018; photo by E.A. Dzyubenko).

A serious problem when growing guar for grain under unfavorable conditions for the crop is incomplete seed ripening, which manifests itself, in particular, in the unformed seed coat. During the period of autumn temperature decrease and high humidity, the seeds in the beans turn black (Fig. 2). In this case, one can observe different ratios of ripened, with a normally formed seed coat and with its color characteristic of the genotype, and dark-colored immature seeds in the harvest. This is the first time this problem has been encountered in the United States. Black seed coat has been shown to be caused by external factors [58]. It was later established that seeds with blackened seed coats have a mature endosperm with the usual content of galactomannan; laboratory germination of blackened and light-colored seeds turned out to be close [59]. However, since the seed coat of blackened seeds is not properly formed, they absorb moisture more quickly and cannot be stored for a long time.

In Russia, the phenomenon of blackening of seeds was observed when growing guar in the Krasnodar Territory in a number of areas, including at the Kuban experimental station of the VIR during late harvesting (see Fig. 2). If there are black seeds in industrial crops, it is recommended to sort the seed material using optical separators [60]. To avoid this problem, the earliest ripening varieties should be used in production crops.

Early maturity is largely determined by photoperiod sensitivity. Guar is a plant with a short photoperiod. The critical duration of the photoperiod in different guar varieties varies from 12-13 to 13-15 hours; with longer daylight hours, plants begin flowering with a strong delay, although there are also genotypes that are weakly sensitive to photoperiod [61]. In the Krasnodar Territory and Rostov Region, where the main guar crops in the Russian Federation are located, the duration of daylight hours in May-June varies between 14.3-15.6 hours.

In the VIR guar collection, polymorphism of the species in response to photoperiod was revealed and genotypes contrasting for this trait were found. They studied metabolomic and transcriptomic profiles, which made it possible to determine the sequences of new genes and allelic variants of genes responsible for the photoperiodic response, the timing of the onset of flowering, and the duration of the growing season [62). Key metabolites associated with the onset of flowering in guar have been identified [63]. A transcriptomic-metabolomic analysis of early flowering loci was performed [64], early and late flowering genotypes were determined, and a model of gene regulation of flowering was proposed [62]. The main result of this research for breeding is the identification of material in the gur gene pool for the creation of early ripening varieties.

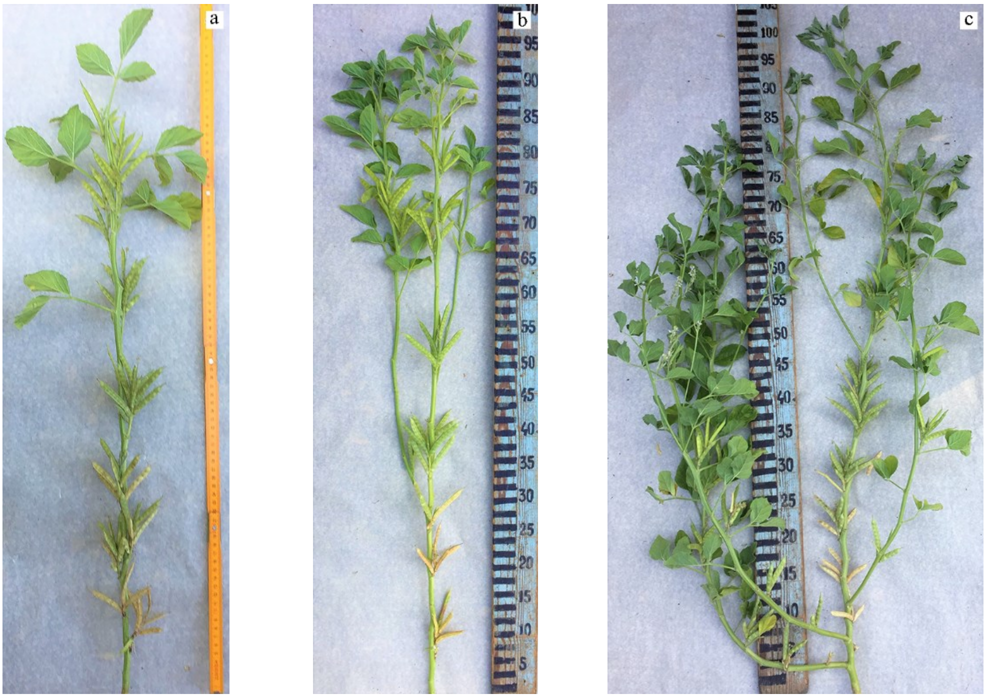

Fig. 3. Samples of guar *Cyamopsis tetragonoloba* (L.) Taub plants from the VIR collection (Vavilov FRC All-Russian Institute of Plant Genetic Resources, St. Petersburg): a — single-stemmed, b — small-stemmed, c — branched (Kuban experimental station VIR, 2018; photo by E.A. Dzyubenko).

The precocity of guar is also associated with plant architecture. The guar gene pool is differentiated into two morphotypes: branching and single-stem (Fig. 3). Branched forms have different types of branching (see Fig. 3, b, c), which were described in detail in the study of samples from the American collection [65]. For varieties of each morphotype, approximate ranges of plant density have been established in order to obtain maximum seed yield. In the conditions of the Krasnodar Territory, this is 200-250 thousand branching and 250-300 thousand single-stem plants per hectare. The yield of branched forms is ultimately slightly higher than that of single-stem forms. However, single-stem guar has a competitive advantage in weed control when planted in dense rows [66]. In addition, beans on single-stemmed plants ripen more evenly, plants can be harvested earlier, which, in conditions of a relatively short summer, makes single-stemmed and small-stemmed forms of guar preferable. Breeders in Italy, India and Portugal have recently paid increasing attention to early maturing single-stem lines [41, 67, 68]). Of the Russian varieties, two varieties bred by VIR, the VIR 1 and Nakhodka belong to the single-stem and small-stem type (see Fig. 3, a, b; Fig. 4, a, b); the varieties Vector and Pobeda are also characterized by one stem (see. Table 2).

At VIR, when creating the Kaspiets variety, forms with a determinant growth type were isolated from varieties of American selection, which favors precocity [69] (see Fig. 4, c). Under US conditions, determinate varieties ripen in 60-90 days, indeterminate varieties in 120-150 days [70].

A number of productive branched varieties of guar have a low location of the first cluster, from 1 to 4 cm from the ground surface, which entails losses during mechanized harvesting. In this regard, the task is to develop varieties with a higher location of the lower fruit node [48, 68]. In thickened crops of single-stem varieties, for example the Vector variety, under conditions of plant competition, the first fruiting node is placed higher [66]. When creating domestic varieties, in particular VIR 1 and Nakhodka, the selection of source material from the VIR collection was carried out, among other things, based on the highest possible location of the first fruit node.

Fig. 4. Single-stem morphotype of the guar Cyamopsis tetragonoloba (L.) Taub in the field (samples from the VIR collection, FRC Vavilov All-Russian Institute of Plant Genetic Resources, St. Petersburg): a — k-52779 from India (Kuban experimental station VIR), b — k-52589, variety Kubansky 1B (Astrakhan experimental station VIR), c — k-54214, variety Kaspiets, branched morphotype with a determinant type of stem growth (2018, photo by E.A. Dzyubenko).

Introduced plants inevitably encounter new diseases and pests. Phytosanitary monitoring of ecological and geographical crops of the VIR guar collection in four geographical locations revealed the main range of guar pests in the Russian Federation. Among the insects, representatives of the family *Aphididae* (true aphids) dominated: the alfalfa aphid *Aphis craccivora* (Koch) and the bean aphid *A. fabae* Scopoli [13]. Aphids are the most harmful because they carry viral infections. After the mass reproduction of aphids on environmental crops, severe focal viral damage to plants, yellowing and marbling of leaves were observed. After insecticidal treatments in August, only single colonies of aphids were detected on the crops [13, 14].

Among fungal diseases, the overwhelming majority of cases were Alternaria blight, caused predominantly by the species *Alternaria tenuissima* (Nees & T. Nees: Fr.) Wiltshire [14]. Analysis of rhizosphere pathogenic mycoflora showed the dominance of fungi from the genera *Verticillium* Nees and Fusarium Link. The most harmful disease of guar, including in the Russian Federation, is bacteriosis (pathogen *Xanthomonas cyamopsidis*). Massive drying out and death of plants was noted in a number of samples. The disease, transmitted through seeds, can lead to the death of plants at all stages of growth and development. Symptoms include large, angular, necrotic lesions on leaf tips that cause defoliation and black streaking on stems. This potentially poses the greatest threat to the guar. Resistant plants have been identified, suggesting the possibility of selecting for individual resistant genotypes [71].

The differential interaction between parasite and host is shown. Therefore, to prevent epiphytoties, varieties protected by non-identical resistance genes should be grown and the maximum possible number of genetically heterogeneous accessions should be involved in breeding.

Heritability and associations of guar productivity traits. The heritability of most productivity traits has been studied, which has made it possible to predict the success of selection for them. Various methods of data analysis were used, including analysis of path coefficients, ANOVA, etc. The additive effect of genes for the following traits was established: the number of branches per plant on the 90th day after sowing, the number of brushes per plant, pod length, bean weight, bean weight on the plant, seed productivity of the plant, gum content in the endosperm of the seed. It is concluded that genetic improvement and selection for these traits will be effective. Low genetic additive variation was observed for traits such as protein content and number of seeds per bean, meaning selection for these traits may be ineffective [72-74]. Low heritability and high environmental influence on the trait number of seeds in a pod, as well as plant height on day 90, were also shown in other studies [41, 75, 76]. The traits number of seeds per bean, number of beans per plant, number of beans per cluster, number of clusters per plant, number of days to 50% flowering, number of days to ripening have significant positive correlations with seed productivity [68].

In experiments on 43 guar samples conducted in the Indian state of Karnataka, the additive genetic variation (GAM) and heritability of traits that make up guar yield were determined. The coefficient of variation indicates how much variation is present in the germplasm for various traits, but heritability coefficients are useful in predicting the success of selection. In the experiment, high (more than > 80%) heritability was noted for the traits number of branches on the plant, type of growth, number of days before flowering, number of clusters on the plant, number of beans on the plant, weight of 100 seeds, gum content in the endosperm (65). The high heritability of the traits the number of days before beans ripen and the number of beans per plant was also established in other works [41, 75, 76].

When studying the mechanism of inheritance of guar gum content, it was found that the manifestation of the trait is under the control of additive, dominant and epistatic effects of genes and is modified by external factors [77].

In none of the guar cultivation areas in the Russian Federation were nitrogen-fixing nodules found on its roots. This is explained by the absence of bacteria in the soil that can enter into symbiosis with guar. Meanwhile, inoculation of legume seeds with biological preparations of root nodule bacteria provides intensive biological nitrogen fixation, which enhances photosynthesis, increases yield, protein content in seeds and green mass, etc. [78]. Based on this, another significant trait for legumes was introduced into the list of selectively significant traits—efficiency of interaction with beneficial soil bacteria (ESBM) [79, 80]. This is especially important when cultivating legumes in new territories, the soils of which do not contain the necessary microsymbionts. For the successful introduction of guar to Russia, along with the above-described measures to improve the culture, selection of effective microsymbionts is required for the purpose of creating biological products.

Scientists from the All-Russian Research Institute for Agricultural Microbiology (ARRIAM, St. Petersburg) was able to identify in the rhizosphere of guar grown in a vegetation experiment with the addition of soil from India, nitrogen-fixing bacteria of two species, the *Bradyrhizobium retamae* and *Ensifer aridi*, which were characterized, patented by the authors and deposited in the Departmental collection beneficial microorganisms for agricultural purposes (ARRIAM) [81, 82]. Both strains showed the ability to form an effective symbiosis with guar and the promise of their further testing in field experiments with the aim of creating biological products to improve the nitrogen nutrition of plants.

Thus, when breeding domestic varieties of guar, a new introduced species on the territory of the Russian Federation, the set of key traits that require improvement is dictated by the main limiting factors for the cultivation of this tropical crop in new soil and climatic conditions. These include: lack of heat and, in some places, moisture supply, long photoperiod, the presence of pathogens, and the absence of nitrogen-fixing microsymbionts in the soil. This determines the search in the gene pool as the starting material for the selection of guar forms with reduced photosensitivity, a short growing season, resistant to certain and/or complex pathogens, and also requires the creation and use of complementary rhizobial preparations. This approach will contribute to the production of productive genotypes that have time to form full-fledged seeds under relatively short summer conditions. The main sign of guar seed productivity is the number of beans on the plant, which determines the yield and yield of gum both from the plant and from industrial crops. Single-stem and low-branched forms are recognized as the best morphotype for Russian conditions, which ensure uniform distribution of beans, suitability for mechanized harvesting and early ripening. The combination of the listed characteristics in one genotype corresponds to the model of an industrial guar variety for the conditions of our country. The created domestic varieties of guar were obtained using traditional breeding methods, but the active development of genomic, metabolomic and transcriptomic resources of the species allows us to hope that in the foreseeable future varieties of this valuable crop for the Russian Federation will be created using marker-mediated and genomic selection.

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