The effect of growing conditions and the year of reproduction on sowing qualities of seeds, morphological and physiological characteristics in sprouts of *Vigna radiata* (L.) R. Wilczek

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**Background.** Mung bean (*Vigna radiata* (L.) R. Wilczek) sprouts are of high nutritional value and are very popular in the world, as they are a source of nutrients and bioactive compounds. In Russia, the consumption of *V. radiata* sprouts is only beginning to develop. Growing this crop for microgreens on a commercial scale requires cultivars with a rapid development rate and higher weight of sprouts. With this in view, the aim of this research was to study the effect of growing conditions and the genotype on morphological and physiological parameters of mung bean seeds and sprouts.

**Methods.** Mung bean accessions from the VIR collection were analyzed. Germination energy, seed germination and seed vigor, and morphological characteristics were evaluated in seeds and sprouts of 16,000 plants. Four plant reproductions grown at Astrakhan (2015, 2017), Kuban (2005) and Adler (2016) Experiment Stations of VIR were studied. The effect produced by growing conditions and the genotype on morphological and physiological parameters of plants was identified using one- and two-way analyses of variance. Correlations between the traits were assessed using correlation and component analyses. **Results.** Specific individual features of the accessions produced the strongest effect on morphological and physiological characteristics of seeds and sprouts; weather conditions, the place and year of reproduction, to a lesser extent. Sowing quality of seeds depended more on the precipitation amount during the growing season than on the sum of active temperatures. When formed under dry conditions, seeds manifested better seed germination, germination energy of seeds, and seed vigor. Accessions with high and stable levels of seed germination, germination energy, and seed vigor, and weight of sprouts were identified.

**Key words:** mung bean, seed germination, germination energy of seeds, seed vigor, effect of ecogeographic conditions, variability of morphological characters.

**Introduction**

Mung bean (*Vigna radiata* (L.) R. Wilczek) is a multipurpose crop, widespread in the countries of Southeast Asia and in the arid regions of Africa and Australia. In the Russian Federation it has been cultivated on small areas in the southern parts of the country. This crop is grown for seeds, sprouts and beans, used to prepare porridge, soups, or vegetable accompaniments. Mung bean dishes enrich the human diet not only with proteins, carbohydrates or micronutrients, but also with essential amino acids, such as lysine, known to be deficient in cereals (Shi et al., 2016). Nutritive value is found not only in seeds, but also in sprouts: because of their low glycemic index they are often used in various diets. Like seeds, they are a source of numerous nutrients. They contain flavonoids, phenolic acids, organic acids, amino acids, carbohydrates, and...
lipids. Metabolites in mung bean sprouts are biologically active and possess antioxidant, antimicrobial, anti-inflammatory, anti-diabetic, antihypertensive, antitumor and other health-friendly properties. That is why ordinary food prepared from mung bean seeds or sprouts is regarded and used as a medication (Tang et al., 2014, Ullah et al., 2014).

Mung bean sprouts (microgreens) are a very popular food among both Europeans and Americans because it serves as a source of minerals and vitamins and its production does not require much acreage, inputs or time (Ebert, 2015; Kyriacou et al., 2016). Sprouts are sold fresh or canned (Pataczek et al., 2018). From 2014 through 2018, the total imports of mung bean seeds to Europe to produce sprouts have been 21–27 million tons (Market Access Database, 2018). In 2017, the main suppliers were Myanmar (14.4 million tons), China (3.8), and Australia (1.9).

In Russia, mung bean sprouts have only recently started to be part of the diet. To cultivate V. radiata on a large scale for microgreen production, it is essential to have cultivars with high plant growth vigor, rapid development rate, and ability to produce large amounts of sprouts.

Seeds with high sowing qualities are quicker to form sprouts. Seed vigor is associated with the growth, development and productivity of plants grown from them (Likhachev, 1984). It is known that seed germination, germination energy of seeds, and seed vigor in many pulse crop seeds depends on cultivar-specific differences and growing conditions (Adamova, 1971a; Likhachev, Shevchenko, 1975; Rakovskaya et al., 2019).

Considering all this, the aim of our research was to analyze the effect produced by seed growing conditions, periods of seed conservation, and specific features of varieties (genotype) on the indicators of seed germination, germination energy, and seed vigor as well as on morphological characters of mung bean sprouts.

The research objectives included:
1. studying the variability in germination energy, seed germination, and seed vigor when seed accessions were reproduced under different ecogeographic conditions;
2. assessing the variability of morphological and agromonic characteristics in sprouts (in the phase of first leaf development) grown from seeds in different sites of reproduction;
3. analyzing the effect of the genotype, weather conditions, place and year of seed reproduction on the studied indicators in seeds and sprouts;
4. identifying mung bean accessions with high and stable levels of the development (growth) and weight of sprouts.

Materials and methods

The accessions of Kenyan origin from the mung bean collection held by the N.I. Vavilov Institute of Plant Genetic Resources (VIR) served as the material for our experiments. The seeds selected for the study were grown under different ecogeographic conditions at three branch stations of VIR: Kuban Experiment Station (KES) in 2005; Astrakhan Experiment Station (AES) in 2015 and 2017; and Adler Experiment Station (AdES) in 2016.

The areas where the seeds were reproduced differed in their soil and climate environments. AES is situated in Astrakhan Province, in the area of insufficient humidity. Soils on the experimental plot are alluvial-meadow heavy loams. The summer is hot and dry. The sum of active temperatures in 2015 was 3945.5°C; in 2017, 3915.7°C; precipitation amount from April to October in 2015 was 92.8 mm; in 2017, 103.0 mm (Fig. 1). KES is located in the steppe area of the Kuban Plain, Krasnodar Territory. Soils in the station’s zone are represented by massive Ciscaucasian chernozems developed on forest-like loam carbonate. The climate in the station’s vicinity is warm, moderately continental, with hot summers, insufficient humidity, and extreme instability in all climatic data elements. In 2005, the sum of active temperatures reached 3751.4°C; precipitation amount from April to October was 346.8 mm. AdES is situated in Adlersky District, City of Sochi, on the shore of the Black Sea. The earth in the vicinity is represented by yellow and red soils. The climate in the station’s area is humid sub-

Fig. 1. The sums of active temperatures and precipitation during the growing season in the years of seed reproduction at the Experiment Stations of VIR: KES – Kuban Experiment Station, AES – Astrakhan Experiment Station, AdES – Adler Experiment Station

Рис. 1. Сумма активных температур и количество осадков, выпавших за вегетационный период в годы размножения семян на опытных станциях ВИР. KES – Кубанская опытная станция, AES – Астраханская опытная станция, AdES – Адлерская опытная станция
tropical, with a hot and humid climatic summer. The sum of active temperatures in 2016 was 4094.7°С, with the precipitation amount from April to October 778.7 mm.

Sums of active temperatures and precipitation amounts were calculated using the weather report data provided by the All-Russia Research Institute of Hydrometeorological Information – World Data Center (RIHMI–WDC, 2020).

Germination energy of seeds and seed germination were measured according to the guidelines approved for grain legume crops (GOST 12038-84). Seeds were germinated in rolls under laboratory conditions at a constant temperature of +20°C. They were placed on two layers of filter paper sized 20 × 100 cm (± 2 cm), 5 cm below the upper edge of a sheet. From above, the sample was covered with a band of moistened filter paper of the same size. Then, the seeds placed between paper layers were rolled up into a roll and inserted vertically into a seed germinator. Seed vigor was analyzed on the basis of B.S. Likhachev’s technique developed for cereal crops (Likhachev, 1975). Seed germination energy indicators were recorded on the 4th day, seed vigor on the 5th, seed germination and seed hardness on the 10th. Germination energy, seed germination, and seed vigor were calculated in percent form. Morphological characters of the sprouts (their wet and dry weight, lengths of the root, stem and first leaf, stem diameter) were examined on the 10th day. For each accession of the collection, 1600 plants were analyzed (100 seeds in 4 replications from each reproduction). All in all, 16,000 plants were evaluated.

Statistical processing of the data obtained was performed using the software package Statistica 10.0 (http://statsoft.ru). To study the relationships between characters, correlation analysis was applied (r is the Pearson correlation coefficient). The following scale was accepted for correlation coefficients: very strong, $r > 0.90$; strong, $0.90 > r > 0.70$; medium, $0.70 > r > 0.50$; and weak, $0.50 > r > 0.30$. Factor analysis (employing principal components) was applied to disclose the variability and structure of relationships among characters.

Statistical significance of the effect produced by the genotype, weather conditions and reproduction sites on the studied characteristics was determined using one-way and two-way analyses of variance. Following Fisher’s model, the percent of the factor’s effect size ($\eta^2$, %) was calculated according to the formula (Ivanter, Korosov, 2003):

$$\eta^2 = \frac{SS_{factor}}{SS_{total}} \times 100\%,$$

where $\eta^2$, % is the effect size percentage; $SS_{factor}$ is the sum of squared deviations for a factor; $SS_{total}$ is the total sum of squared deviations.

**Results and discussion**

Our research has shown that the mung bean accessions from Kenya demonstrate high variability in their growth and development indicators in the early stages of plant ontogenesis (Table 1). Strong variations were observed in morphological (root length, stem length, leaf length, and stem diameter) and agronomic (1000 seed weight, and sprout weight) characters as well as in physiological ones (germination energy of seeds, seed germination, and seed vigor).

| Indicator                        | Minimum value | Maximum value | Mean value, error of the mean |
|----------------------------------|---------------|---------------|-----------------------------|
| Germination energy of seeds, %   | 18.00         | 100.00        | 75.89 ± 0.78                |
| Seed germination, %              | 22.00         | 100.00        | 80.31 ± 0.70                |
| Seed vigor, %                    | 0.00          | 96.00         | 45.81 ± 1.16                |
| Seed hardness, %                 | 0.00          | 30.00         | 3.22 ± 0.22                 |
| 1000 seed weight, g             | 24.00         | 138.00        | 50.83 ± 0.87                |
| Wet sprout weight, g             | 0.13          | 0.60          | 0.34 ± 0.01                 |
| Dry sprout weight, g             | 0.01          | 0.06          | 0.03 ± 0.0004               |
| Sprout stem length, cm           | 2.80          | 17.60         | 8.51 ± 0.01                 |
| Sprout root length, cm           | 2.00          | 19.20         | 11.67 ± 0.12                |
| Sprout stem diameter, mm         | 1.00          | 5.00          | 2.48 ± 0.03                 |
| First leaf length, cm            | 0.50          | 3.10          | 1.75 ± 0.14                 |
The studied characters varied greatly across the places of seed reproduction (Fig. 2). Practically all measured indicators showed the best values in the seeds and sprouts produced in Astrakhan Province (AES). Those accessions had the highest germination energy, seed germination, and seed vigor. They also exceeded accessions grown at other sites in the weight of wet sprouts, stem and root lengths, but in the first leaf length they were the best only in 2015. Seeds produced at the Kuban Experiment Station had the highest weight of 1000 seeds, but the sprouts germinated from them demonstrated lower values of root, stem and leaf length, and wet sprout weight. The exceptions were stem diameter and dry sprout weight: these indicators showed higher values than in the sprouts grown from the seeds of other reproductions. The worst values were observed in the seeds and sprouts produced in Adler (AdES).

Fig. 2. Variability of growth and development indicators in the sprouts of *Vigna radiata* grown from seeds reproduced in different soil and climate environments

Fig. 2. Изменчивость показателей роста и развития проростков *Vigna radiata*, выращенных из семян, репродуцированных в разных почвенно-климатических условиях
In our experiment, significant differences in morphological, biological and agronomic characteristics were registered between different accessions as well (Table 2). The best mean values (calculated for all versions of the experiment) of germination energy and seed germination were found in accessions k-14436, k-14401, k-14408 and k-14451, while k-14407, k-14436 and k-14403 were the best in seed vigor. Among those accessions k-14407 deserves a special mention as it stably demonstrated good seed growth values regardless of the year or place of seed reproduction. The highest seed hardness was observed in k-14416; the same accession showed low levels of germination energy, seed germination, and seed vigor. An analogous pattern of the abovementioned indicators was obvious in k-14421. High values of root length were identified in accessions k-14408, k-14436 and k-14438; stem length, in k-14408; leaf length, in k-14408, k-14438 and k-14403; stem diameter, in k-14401, k-14438 and k-14403; wet sprout weight, in k-14408, k-14438, k-14403 and k-14436; dry sprout weight, in k-14408 and k-14403. The best accessions in the entire set of indicators were k-14408, k-14403 and k-14438.

To check the significance of the effect produced by the genotype, place and year of reproduction, and weather conditions on the tested indicators, factorial analysis of variance was applied (Tables 3–6). Its results showed that the variability of the studied characters was significantly affected by all the factors in question. Seed hardness, however, did not depend on the site of seed reproduction. In our experiment, this indicator was stronger influenced by the genotype (effect size $\eta^2 = 42\%$), and to a lesser extent by the year of seed reproduction ($\eta^2 = 1\%$).

Two-way analysis of variance, undertaken to disclose associations between the year of seed reproduction and the genotype, and the variability of morphological and agronomic characters, showed that the latter were more affected by the genome of an accession than the year of its reproduction (Table 3). The effect size of the genotype, produced on 1000 seed weight, was 58%; on wet and dry sprout weight, 65 and 57%, respectively; on root, leaf and stem lengths, 33, 31 and 34%, respectively; on stem diameter, 25%. The genotype and the year of seed reproduction had almost the same effect on the variability of sowing quality indicators in mung bean seeds (germination energy, seed germination, and seed vigor); their effect size varied within the range of 24 to 36%.

According to the results of a one-way analysis of variance, the site of seed reproduction rendered an effect on the growth indicators of seeds and sprouts in a similar way as with the year of their reproduction (Table 4). Tukey’s test showed that soil and climate conditions at AdES and KES had an almost similar effect on the studied indicators, while AES was significantly different. In the context of the analyzed set of morphological and physiological characters, the seeds delivered from Astrakhan Province were much better

Fig. 2. Variability of growth and development indicators in the sprouts of Vigna radiata grown from seeds reproduced in different soil and climate environments

Рис. 2. Изменчивость показателей роста и развития проростков Vigna radiata, выращенных из семян, апродуцированных в разных почвенно-климатических условиях
Table 3. Results of a two-way analysis of variance, disclosing associations between the year of seed reproduction and the genotype, and the variability of morphological and biological characters in *Vigna radiata* (2005, 2015-2017)

Таблица 3. Результаты двухфакторного дисперсионного анализа по выявлению ассоциаций между годом репродукции семян, генотипом и изменчивостью морфологических и биологических признаков *Vigna radiata* (2005, 2015-2017 гг.)

| Catalogue No. | Germination energy of seeds, % | Seed germination, % | Seed vigor, % | Seed hardness, % | 1000 seed weight, g | Wet sprout weight, g | Dry sprout weight, g | Stem length, cm | Root length, cm | Stem diameter, mm | Leaf length, cm |
|---------------|--------------------------------|---------------------|---------------|------------------|---------------------|---------------------|--------------------|-----------------|----------------|-----------------|----------------|
| 14401         | 86.3                           | 87.8                | 21.8          | 0.2              | 39.6                | 0.3                 | 0.03               | 6.8             | 10.8           | 3.3             | 1.8            |
| 14403         | 69.8                           | 79.0                | 64.7          | 0.1              | 60.2                | 0.4                 | 0.04               | 6.5             | 8.6            | 2.8             | 1.9            |
| 14405         | 79.7                           | 85.0                | 35.3          | 0.3              | 48.3                | 0.3                 | 0.03               | 7.9             | 10.1           | 2.7             | 1.8            |
| 14407         | 78.8                           | 82.7                | 76.7          | 7.5              | 34.5                | 0.3                 | 0.02               | 9.2             | 13.4           | 2.5             | 1.8            |
| 14408         | 84.2                           | 90.0                | 60.8          | 0.9              | 94.0                | 0.5                 | 0.04               | 11.6            | 14.1           | 2.7             | 2.2            |
| 14412         | 79.9                           | 82.4                | 44.6          | 3.0              | 70.0                | 0.3                 | 0.02               | 8.9             | 12.9           | 2.3             | 1.5            |
| 14416         | 47.5                           | 52.7                | 26.0          | 14.9             | 51.3                | 0.2                 | 0.02               | 6.5             | 12.4           | 2.0             | 1.5            |
| 14421         | 64.8                           | 69.5                | 33.5          | 5.9              | 35.5                | 0.3                 | 0.02               | 7.7             | 9.6            | 2.1             | 1.4            |
| 14436         | 95.5                           | 96.5                | 68.0          | 1.5              | 60.0                | 0.4                 | 0.02               | 10.3            | 14.1           | 2.0             | 1.8            |
| 14438         | 75.3                           | 79.5                | 33.7          | 0.0              | 34.7                | 0.5                 | 0.03               | 13.6            | 2.9            | 1.9             |
| 14451         | 84.4                           | 88.0                | 57.8          | 0.9              | 40.4                | 0.3                 | 0.03               | 9.1             | 11.3           | 2.1             | 1.8            |

Table 2. Characterization of *Vigna radiata* accessions according to mean values of their growth and development indicators in the early stages of ontogenesis at the Kuban, Astrakhan, and Adler Experiment Stations of VIR (2005, 2015-2017)

Таблица 2. Характеристика образцов *Vigna radiata* по средним показателям роста и развития растений на ранних стадиях онтогенеза на Кубанской, Астраханской и Адлерской опытных станциях ВИР (2005, 2015-2017 гг.)

| Catalogue No. | Germination energy of seeds, % | Seed germination, % | Seed vigor, % | Seed hardness, % | 1000 seed weight, g | Wet sprout weight, g | Dry sprout weight, g | Stem length, cm | Root length, cm | Stem diameter, mm | Leaf length, cm |
|---------------|--------------------------------|---------------------|---------------|------------------|---------------------|---------------------|--------------------|-----------------|----------------|-----------------|----------------|
| 14401         | 86.3                           | 87.8                | 21.8          | 0.2              | 39.6                | 0.3                 | 0.03               | 6.8             | 10.8           | 3.3             | 1.8            |
| 14403         | 69.8                           | 79.0                | 64.7          | 0.1              | 60.2                | 0.4                 | 0.04               | 6.5             | 8.6            | 2.8             | 1.9            |
| 14405         | 79.7                           | 85.0                | 35.3          | 0.3              | 48.3                | 0.3                 | 0.03               | 7.9             | 10.1           | 2.7             | 1.8            |
| 14407         | 78.8                           | 82.7                | 76.7          | 7.5              | 34.5                | 0.3                 | 0.02               | 9.2             | 13.4           | 2.5             | 1.8            |
| 14408         | 84.2                           | 90.0                | 60.8          | 0.9              | 94.0                | 0.5                 | 0.04               | 11.6            | 14.1           | 2.7             | 2.2            |
| 14412         | 79.9                           | 82.4                | 44.6          | 3.0              | 70.0                | 0.3                 | 0.02               | 8.9             | 12.9           | 2.3             | 1.5            |
| 14416         | 47.5                           | 52.7                | 26.0          | 14.9             | 51.3                | 0.2                 | 0.02               | 6.5             | 12.4           | 2.0             | 1.5            |
| 14421         | 64.8                           | 69.5                | 33.5          | 5.9              | 35.5                | 0.3                 | 0.02               | 7.7             | 9.6            | 2.1             | 1.4            |
| 14436         | 95.5                           | 96.5                | 68.0          | 1.5              | 60.0                | 0.4                 | 0.02               | 10.3            | 14.1           | 2.0             | 1.8            |
| 14438         | 75.3                           | 79.5                | 33.7          | 0.0              | 34.7                | 0.5                 | 0.03               | 13.6            | 2.9            | 1.9             |
| 14451         | 84.4                           | 88.0                | 57.8          | 0.9              | 40.4                | 0.3                 | 0.03               | 9.1             | 11.3           | 2.1             | 1.8            |

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Таблица 3. Окончание

| Factors          | Df | SS  | MS  | F    | p   | SS  | MS  | F    | p   |
|------------------|----|-----|-----|------|-----|-----|-----|------|-----|
| Seed vigor       |    |     |     |      |     |     |     |      |     |
| Genotype         | 9  | 226834 | 22683 | 68.996 | 0.00 | 217927 | 21793 | 120.841 | 0.00 |
| Year             | 3  | 237043 | 79014 | 240.337 | 0.00 | 34650 | 11550 | 64.046 | 0.00 |
| Residual variability | 686 | 225533 | 329  |       |     | 123715 | 180  |       |     |
| Total variability | 699 | 663876 | 373978 |     |     |       |     |      |     |
| η²_genotype %   | 34.17 |      |     |      |     | 58.27 |      |     |     |
| η²_year %       | 35.71 |      |     |      |     | 9.27  |      |     |     |
| Wet sprout weight|    |     |     |      |     |     |     |      |     |
| Genotype         | 9  | 4.54774 | 0.45477 | 183.03 | 0.00 | 0.043590 | 0.004359 | 135.48 | 0.00 |
| Year             | 3  | 1.09719 | 0.36573 | 147.20 | 0.00 | 0.008128 | 0.002709 | 84.20  | 0.00 |
| Residual variability | 686 | 1.70447 | 0.00248 |     |     | 0.022073 | 0.000032 |       |     |
| Total variability | 699 | 7.01786 |      |      |     | 0.076446 |     |      |     |
| η²_genotype %   | 64.80 |      |     |      |     | 57.02  |      |     |     |
| η²_year %       | 15.63 |      |     |      |     | 10.63  |      |     |     |
| Dry sprout weight|    |     |     |      |     |     |     |      |     |
| Stem length      |    |     |     |      |     |     |     |      |     |
| Genotype         | 9  | 1613.01 | 161.30 | 50.24 | 0.00 | 2251.74 | 225.17 | 41.55  | 0.00 |
| Year             | 3  | 958.62  | 319.54 | 99.52 | 0.00 | 907.62  | 302.54 | 55.83  | 0.00 |
| Residual variability | 686 | 2202.66 | 3.21  |     |     | 3717.39 | 5.42  |       |     |
| Total variability | 699 | 4770.26 |      |      |     | 6831.78 |     |      |     |
| η²_genotype %   | 33.81 |      |     |      |     | 32.96  |      |     |     |
| η²_year %       | 20.10 |      |     |      |     | 13.29  |      |     |     |
| Root length      |    |     |     |      |     |     |     |      |     |
| Stem diameter    |    |     |     |      |     |     |     |      |     |
| Genotype         | 9  | 88.354 | 8.835 | 29.45 | 0.00 | 30.718  | 3.072  | 36.89  | 0.00 |
| Year             | 3  | 40.177 | 13.392 | 44.64 | 0.00 | 11.134  | 3.711  | 44.57  | 0.00 |
| Residual variability | 686 | 205.791 | 0.300 |     |     | 57.127  | 0.083  |       |     |
| Total variability | 699 | 354.990 |      |      |     | 99.983  |     |      |     |
| η²_genotype %   | 24.89 |      |     |      |     | 30.72  |      |     |     |
| η²_year %       | 11.32 |      |     |      |     | 11.14  |      |     |     |

SS – sum of squares; MS – mean squares; F – Fisher criterion value; p – significance level; df – degrees of freedom, η², % – effect size, percentage
SS – сумма квадратов, MS – среднеквадратичное отклонение, F – значение критерия Фишера, p – уровень значимости, df – числа степеней свободы, η², % – доля влияния
Table 4. Results of a one-way analysis of variance, disclosing associations between the variability of morphological and biological characters in *Vigna radiata* and the site of seed reproduction

| Factors                  | Df  | SS     | MS     | F   | p    | SS     | MS     | F   | p    |
|--------------------------|-----|--------|--------|-----|------|--------|--------|-----|------|
| **Germination energy of seeds** |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 83864  | 41932  | 134.75 | 0.00 | 63276  | 31638  | 122.61 | 0.00 |
| Residual variability    | 597 | 216892 | 311    |       |      | 179847 | 258    |      |      |
| Total variability       | 599 | 300756 |        |       |      | 243124 |        |      |      |
| η², %                   |     | 27.88  |        |      |      | 26.03  |        |      |      |
| **Seed germination**    |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 193028 | 96514  | 142.870 | 0.00 | 30819  | 15410  | 31.299 | 0.00 |
| Residual variability    | 597 | 470848 | 676    |       |      | 343159 | 492    |      |      |
| Total variability       | 599 | 663876 |        |       |      | 373978 |        |      |      |
| η², %                   |     | 29.08  |        |      |      | 8.24   |        |      |      |
| **Wet sprout weight**   |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 0.75041 | 0.37521 | 41.727 | 0.00 | 0.007069 | 0.003534 | 35.509 | 0.00 |
| Residual variability    | 597 | 6.26744 | 0.00899 |       |      | 0.069377 | 0.000100 |      |      |
| Total variability       | 599 | 7.01786 |        |       |      | 0.076446 |        |      |      |
| η², %                   |     | 10.69  |        |      |      | 9.25   |        |      |      |
| **Dry sprout weight**   |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 938.88 | 469.44 | 85.400 | 0.00 | 824.75 | 412.37 | 47.85  | 0.00 |
| Residual variability    | 597 | 3831.38 | 5.50    |       |      | 6007.04 | 8.62   |      |      |
| Total variability       | 599 | 4770.26 |        |       |      | 6831.78 |        |      |      |
| η², %                   |     | 19.68  |        |      |      | 12.07  |        |      |      |
| **Stem length**         |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 34.174 | 17.087 | 37.123 | 0.00 | 7.853  | 3.927  | 29.71  | 0.00 |
| Residual variability    | 597 | 320.815 | 0.460   |       |      | 92.130 | 0.132  |      |      |
| Total variability       | 599 | 354.990 |        |       |      | 99.983 |        |      |      |
| η², %                   |     | 9.63   |        |      |      | 7.85   |        |      |      |
| **Root length**         |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 34.174 | 17.087 | 37.123 | 0.00 | 7.853  | 3.927  | 29.71  | 0.00 |
| Residual variability    | 597 | 320.815 | 0.460   |       |      | 92.130 | 0.132  |      |      |
| Total variability       | 599 | 354.990 |        |       |      | 99.983 |        |      |      |
| η², %                   |     | 9.63   |        |      |      | 7.85   |        |      |      |
| **Stem diameter**       |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 34.174 | 17.087 | 37.123 | 0.00 | 7.853  | 3.927  | 29.71  | 0.00 |
| Residual variability    | 597 | 320.815 | 0.460   |       |      | 92.130 | 0.132  |      |      |
| Total variability       | 599 | 354.990 |        |       |      | 99.983 |        |      |      |
| η², %                   |     | 9.63   |        |      |      | 7.85   |        |      |      |
| **Leaf length**         |     |        |        |     |      |        |        |     |      |
| Place of reproduction    | 2   | 34.174 | 17.087 | 37.123 | 0.00 | 7.853  | 3.927  | 29.71  | 0.00 |
| Residual variability    | 597 | 320.815 | 0.460   |       |      | 92.130 | 0.132  |      |      |
| Total variability       | 599 | 354.990 |        |       |      | 99.983 |        |      |      |
| η², %                   |     | 9.63   |        |      |      | 7.85   |        |      |      |
in their quality than those grown on the experimental fields of Krasnodar Territory.

The sum of active temperatures and the amount of precipitation during the growing season had a statistically significant effect on the variability of all tested characteristics of mung bean seeds and sprouts (Tables 5, 6). The effect of these two factors on seed germination energy, seed germination, and seed vigor was higher than on other characters: the effect size percentage varied from 27 to 32%. Their effect on morphological and agronomic traits was 8–20%. The

**Table 5. Results of a one-way analysis of variance, disclosing associations between the variability of morphological and biological characters in Vigna radiata and the sum of active temperatures**

| Factors                        | Df | SS   | MS   | F       | p     | SS   | MS   | F       | p     |
|--------------------------------|----|------|------|---------|-------|------|------|---------|-------|
| **Germination energy of seeds** |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 87817| 29272| 95.68   | 0.00  | 65090| 21697| 84.82   | 0.00  |
| Residual variability           | 696| 212940| 306  |         |       | 178034| 256  |         |       |
| Total variability              | 699| 300756|      |         |       | 243124|      |         |       |
| \( \eta^2 \) %                 | 29.20| 26.77|      |         |       |       |      |         |       |
| **Seed vigor**                 |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 212018| 70673| 108.857| 0.00  | 33278| 11093| 22.661  | 0.00  |
| Residual variability           | 696| 451858| 649  |         |       | 340700| 490  |         |       |
| Total variability              | 699| 663876|      |         |       | 373978|      |         |       |
| \( \eta^2 \) %                 | 31.94| 8.90|      |         |       |       |      |         |       |
| **1000 seed weight**           |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 0.75513| 0.25171| 27.974 | 0.00  | 0.010591| 0.003530| 37.313  | 0.00  |
| Residual variability           | 696| 6.26272| 0.00900|         |       | 0.065854| 0.000095|         |       |
| Total variability              | 699| 7.01786|      |         |       | 0.076446|      |         |       |
| \( \eta^2 \) %                 | 10.76| 8.90|      |         |       |       |      |         |       |
| **Wet sprout weight**          |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 954.95| 318.32| 58.068 | 0.00  | 853.53| 284.51| 33.12   | 0.00  |
| Residual variability           | 696| 3815.32| 5.48  |         |       | 5978.25| 8.59  |         |       |
| Total variability              | 699| 4770.26|      |         |       | 6831.78|      |         |       |
| \( \eta^2 \) %                 | 20.02| 12.49|      |         |       |       |      |         |       |
| **Dry sprout weight**          |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 59.588| 19.863| 46.799 | 0.00  | 11.459| 3.820 | 30.03   | 0.00  |
| Residual variability           | 696| 295.402| 0.424 |         |       | 88.524| 0.127 |         |       |
| Total variability              | 699| 354.990|      |         |       | 99.983|      |         |       |
| \( \eta^2 \) %                 | 16.79| 11.46|      |         |       |       |      |         |       |
| **Stem length**                |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 954.95| 318.32| 58.068 | 0.00  | 853.53| 284.51| 33.12   | 0.00  |
| Residual variability           | 696| 3815.32| 5.48  |         |       | 5978.25| 8.59  |         |       |
| Total variability              | 699| 4770.26|      |         |       | 6831.78|      |         |       |
| \( \eta^2 \) %                 | 20.02| 12.49|      |         |       |       |      |         |       |
| **Root length**                |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 59.588| 19.863| 46.799 | 0.00  | 11.459| 3.820 | 30.03   | 0.00  |
| Residual variability           | 696| 295.402| 0.424 |         |       | 88.524| 0.127 |         |       |
| Total variability              | 699| 354.990|      |         |       | 99.983|      |         |       |
| \( \eta^2 \) %                 | 16.79| 11.46|      |         |       |       |      |         |       |
| **Leaf length**                |    |      |      |         |       |      |      |         |       |
| Sum of active temperatures     | 3  | 59.588| 19.863| 46.799 | 0.00  | 11.459| 3.820 | 30.03   | 0.00  |
| Residual variability           | 696| 295.402| 0.424 |         |       | 88.524| 0.127 |         |       |
| Total variability              | 699| 354.990|      |         |       | 99.983|      |         |       |
| \( \eta^2 \) %                 | 16.79| 11.46|      |         |       |       |      |         |       |
Table 6. Results of a one-way analysis of variance, disclosing associations between the variability of morphological and biological characters in *Vigna radiata* and the amount of precipitation

Таблица 6. Результаты однофакторного дисперсионного анализа по выявлению ассоциаций между изменчивостью морфологических и биологических признаков *Vigna radiata* и количеством осадков

| Factors                      | Df | SS   | MS   | F    | p    | SS   | MS   | F    | p    |
|------------------------------|----|------|------|------|------|------|------|------|------|
| Germination energy of seeds  |    |      |      |      |      |      |      |      |      |
| Precipitation amount         | 3  | 87900| 29300| 95.80| 0.00 | 65249| 21750| 85.10| 0.00 |
| Residual variability         | 696| 212857| 306  |      |      | 177874| 256  |      |      |
| Total variability            | 699| 300756|      |      |      | 243124|      |      |      |
| η², %                        |    | 29.23|      |      |      | 26.84 |      |      |      |
| Seed germination              |    |      |      |      |      |      |      |      |      |
| Precipitation amount         | 3  | 211509| 70503| 108.474| 0.00 | 32336| 10779| 21.959| 0.00 |
| Residual variability         | 696| 452366| 650  |      |      | 341642| 491  |      |      |
| Total variability            | 699| 663876|      |      |      | 373978|      |      |      |
| η², %                        |    | 31.86|      |      |      | 8.65  |      |      |      |
| 1000 seed weight             |    |      |      |      |      |      |      |      |      |
| Wet sprout weight            |    |      |      |      |      |      |      |      |      |
| Precipitation amount         | 3  | 0.76565| 0.25522| 28.411| 0.00 | 0.010783| 0.003594| 38.098| 0.00 |
| Residual variability         | 696| 6.25221| 0.00898|      |      | 0.065663| 0.000094|      |      |
| Total variability            | 699| 7.01786|      |      |      | 0.076446|      |      |      |
| η², %                        |    | 10.91|      |      |      | 14.11 |      |      |      |
| Dry sprout weight            |    |      |      |      |      |      |      |      |      |
| Stem length                  |    |      |      |      |      |      |      |      |      |
| Precipitation amount         | 3  | 954.59| 318.20| 58.041| 0.00 | 862.65| 287.55| 33.53| 0.00 |
| Residual variability         | 696| 3815.67| 5.48  |      |      | 5969.14| 8.58  |      |      |
| Total variability            | 699| 4770.26|      |      |      | 6831.78|      |      |      |
| η², %                        |    | 20.01|      |      |      | 12.63 |      |      |      |
| Root length                  |    |      |      |      |      |      |      |      |      |
| Precipitation amount         | 3  | 60.845| 20.282| 47.990| 0.00 | 12.138| 4.046 | 32.06| 0.00 |
| Residual variability         | 696| 294.145| 0.423 |      |      | 87.846| 0.126 |      |      |
| Total variability            | 699| 354.990|      |      |      | 99.983 |      |      |      |
| η², %                        |    | 17.14|      |      |      | 12.14 |      |      |      |
precipitation amount produced a little stronger effect on variations in wet and dry sprout weight, stem diameter, and root and leaf length. Correlation analysis identified weak negative correlations between precipitation amount and germination energy of seeds ($r = -0.47$), seed germination ($r = -0.46$), seed vigor ($r = -0.40$), wet sprout weight ($r = -0.30$), stem length ($r = -0.39$), and root length ($r = -0.35$); correlation coefficients were weaker for all other characters ($r < 0.30$). The sum of active temperature correlated very weakly ($r < 0.30$) with all morphological and physiological characters.

Interrelations among morphological and physiological characters were studied using correlation analysis (significance level $p < 0.05$). As a result, strong correlations were identified between germination energy of seeds and seed germination ($r = 0.95$), and dry and wet sprout weights ($r = 0.70$). Germination energy had medium correlations with a number of characters: seed vigor ($r = 0.60$), and sprout stem length ($r = 0.58$). The same correlation level was observed for seed germination with seed vigor ($r = 0.58$), wet sprout weight ($r = 0.50$), stem length ($r = 0.57$), and leaf length ($r = 0.50$). Seed vigor correlated with stem length ($r = 0.56$). Wet sprout weight correlated both with stem length ($r = 0.56$) and with leaf length ($r = 0.59$), while dry sprout weight only with leaf length ($r = 0.59$). Positive correlations were found between stem and root lengths ($r = 0.61$), and between stem and leaf lengths ($r = 0.50$). Negative correlations were observed for seed hardness with germination energy ($r = -0.50$) and seed germination ($r = -0.49$). Thus, sowing qualities of seeds to a considerable extent determined the development of sprouts, while seed hardness reduced the seed germination and germination energy indicators. Maximum weight was measured in sprouts with long stems and leaves.

Factor analysis (employing principal components) was applied to disclose regularities in the variability and structure of links among characters in mung bean accessions in the early stages of ontogenesis (Table 7). Component analysis identified two factors that determined 59.0% of the total variance for characters. The first factor ($F_1$, 35% of variance) included: seed germination, germination energy, seed vigor, wet sprout weight, and stem, root and leaf lengths. Analyzing the first factor showed that the seeds with high values of seed germination, germination energy, seed vigor developed sprouts with a higher wet sprout weight, and longer stems, leaves and roots. This factor may be interpreted as the factor of seed germination energy and seed vigor. The second factor ($F_2$, 24% of variance) aggregated dry sprout weight, stem diameter, 1000 seed weight, and, in negative correlation, seed hardness. The leading characters within this factor, i.e., with the strongest effect on coordinated variations in the rest characters, were dry sprout weight and stem diameter. Studying the set of characters in the second factor revealed an interrelation between stem diameter and 1000 seed weight. Sprouts with a longer stem diameter germinated from larger seeds. Seed hardness was observed more often in small-seeded accessions. It should be mentioned that wet sprout weight was a transgressive character, interlinked not only with seed germination and germination energy, but also with seed weight, i.e., it depended on a coordinated variability in several sets of correlated characters.

Considering the distribution of the tested accessions across the space of the first two factors, it is possible to notice that the plants with similar characters are located close to each other (Fig. 3). Figure 3.1 shows a quite compact group of accessions reproduced at AES in 2017. Accessions grown at AES in 2015 are observed nearby. In the scatter-plot they occupy the area characterized by high values of seed germination, seed germination energy, seed vigor, stem length, root length, leaf length, medium and large seeds, medium and high sprout weights.

Accessions reproduced at KES (2005) are in the area of plants with low or medium values of seed germination, germination energy, seed vigor, large and medium seeds, high and medium weights of dry and wet sprouts. For a majority of accessions reproduced at AdES (2016), minimum levels of seed germination, germination energy and vigor were observed. Most of them are located in the area of small and medium seeds, small sprout weights, short

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**Table 7. Factor loadings of characters in mung bean seeds and sprouts**

| Character                        | Factor 1 | Factor 2 |
|----------------------------------|----------|----------|
| Germination energy of seeds      | 0.85     | 0.17     |
| 1000 seed weight                 | -0.05    | 0.55     |
| Seed germination                 | 0.83     | 0.26     |
| Seed hardness                    | -0.26    | -0.58    |
| Seed vigor                       | 0.81     | -0.15    |
| Wet sprout weight                | 0.55     | 0.64     |
| Dry sprout weight                | 0.22     | 0.82     |
| Sprout stem length               | 0.83     | 0.08     |
| Sprout root length               | 0.62     | 0.04     |
| Sprout stem diameter             | -0.14    | 0.73     |
| Sprout leaf length               | 0.57     | 0.49     |
| Variance, %                      | 35.0     | 24.0     |
Fig. 3. Scatterplot of the tested mung bean accessions in the factorial space.
Factor 1, Factor 2 are the first two factors.
1. Across the stations, where 2005 means the seed reproduction at the Kuban Experiment Station (KES); 2015 and 2017 mean the seed reproductions at Astrakhan Experiment Station (AES); 2016 means the seed reproduction at Adler Experiment Station (AdES) of VIR.
2. Across VIR’s catalogues, where ‘k-’ is the catalogue number of an accession.

Рис. 3. Распределение изученных образцов манго в факторном пространстве.
Фактор 1, Фактор 2 – первые два фактора.
1. По станциям, где 2005 – репродукция Кубанской опытной станции; 2015 и 2017 – репродукции Астраханской опытной станции; 2016 – репродукция Адлерской опытной станции – филиалов ВИР.
2. По каталогам ВИР, где «к» – номер каталога.
leaves, stems and roots (in the scatterplot they are to the left, in the lower and middle parts). Accession k-14407 was an exception (on Fig. 3.1 it may be found among the accessions reproduced at AES in 2015 and 2017). This variety demonstrated high seed germination, germination energy and vigor, with medium values in sprout and seed weights, regardless of the year and place of seed reproduction. Accession k-14451 was close to the latter in the tested indicators. Also worth mentioning are k-14401, k-14403 and k-14408 which showed stable high levels in 1000 seed weight and sprout weights in all the years of testing. On the scatterplot they are in the upper part of the image (Fig. 3.2). Accessions k-14405 and k-14412 changed their indicators in different sites of reproduction: they demonstrated the best values of sprout weight when reproduced at KES, while their seed germination, germination energy and vigor were better at AES. Accession k-14416, with the highest percentage of hard seeds per sample (on Fig. 3.2, to the left in the lower and middle area), had the lowest values in seed germination and seed vigor.

While analyzing Fig. 3, it is possible to trace a reduction of seed germination, germination energy and seed vigor levels when mung bean was cultivated in more humid environments (KES or AdES). These characters in a majority of accessions had high values when seed reproduction was performed in dry climate at AES. This is well in line with the cessions had high values when seed reproduction was performed in dry climate at AES. Accession k-14416, with the highest percentage of hard seeds per sample (on Fig. 3.2, to the left in the lower and middle area), had the lowest values in seed germination and seed vigor.

It should be also taken into account that higher humidity combined with higher temperatures accelerates the development of microorganisms on seed surface, which leads to even more rapid reduction and deterioration of seed germination. It should be mentioned that, despite high variations of the studied morphological and physiological indicators and their dependence on the genotype and seed growing conditions, it was possible to identify mung bean varieties with stable and high levels of seed germination, germination energy and vigor, combined with medium sprout weight values: k-14407 and k-14451. As for accessions k-14401, k-14403 and k-14408, they are the best in terms of economic value, as they demonstrated the highest sprout weights, regardless of the site of seed reproduction.

**Conclusion**

The accessions of Vigna radiata from Kenya demonstrated high variability in morphological, agronomic and physiological characteristics of their seeds and sprouts. A statistically significant effect on all these variable characters was produced by the genotype, the year of seed reproduction, and the ecogeographic environments where the seeds were formed. Individual features of the accessions provided the strongest effect on all characteristics; the effect of the site of reproduction and meteorological conditions (precipitation amounts and sums of active temperatures) was less strong. Abundant rainfalls during the plant growing season reduced the sowing qualities of seeds. The dry climate of Astrakhan Province proved to be more favorable for mung bean cultivation.

The effect of weather conditions, recorded during the growing season, on the variability of morphological characters in mung bean sprouts was weaker than on the seed germination indicators.

The weight of a mung bean sprout is correlated with seed germination energy, stem length and diameter, and leaf length. Seed hardiness is negatively correlated with seed germination, germination energy, and seed vigor, and positively correlated with small seed size.

Among the studied accessions, there are mung bean varieties with high and stable indicators of seed germination, germination energy, and seed vigor, morphological characteristics, and weight of sprouts. These varieties are promising for large-scale commercial cultivation of mung bean for microgreen production.

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