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Identification of Modern High-Yield Soybean Genotypes for Potassium-Use Efficiency in Sandy Soil of the Brazilian Cerrado

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Abstract: Soybean is the main leguminous crop in Brazil, mostly grown in tropical soils with low potassium (K) availability. Therefore, the identification of new genotypes with efficient K uptake and utilization in environments with low exchangeable K content is an economically viable alternative to maximize crop yield in Brazil. A study was conducted to investigate the response of 25 modern high-yield soybean genotypes for K-use efficiency in a sandy tropical soil of the Brazilian Cerrado. Treatments were distributed in a completely randomized design in a 2 × 25 factorial scheme: two levels of K fertilization [20 mg K dm^{-3} (low level) or 200 mg K dm^{-3} (high level)] and 25 soybean genotypes with three replicates. Plant morphological traits, leaf K, and crop production components were measured. Based on grain production data, K-use efficiency (KUE) and response efficiency (RE) to K fertilization were calculated. Leaf area, shoot dry matter, pod number per plant, 1000-grain weight, and grain yield were the crop characteristics most limited by low soil K availability. The soybean genotypes "TMG7061 IPRO", "BMX Bônus IPRO", "RK6719 IPRO", and "RK8317 IPRO" were classified as efficient in the use of soil K and are the most suitable genotypes to be cultivated in agricultural soils with low K availability. The genotypes "98R35 IPRO", "HO Maracaí IPRO", "BMX Bônus IPRO", and "RK7518 IPRO" were classified as responsive to K fertilization and are the most recommended genotypes for cultivation in agricultural areas with the application of high K fertilizer rates. The genotype "BMX Bônus IPRO" simultaneously combines characteristics of K-use efficiency and response to K fertilization and hence can be grown in both K-deficient and optimal soils.

Keywords: potassium fertilization; potassium uptake efficiency; potassium deficiency; tropical soil

1. Introduction

Soybeans [*Glycine max* (L.) Merrill.] is one of the main oilseed crops in the world and grows in tropical, subtropical, and temperate climates. Brazil is now the largest producer and exporter of soybean on the planet, and the Cerrado region is responsible for about 55–60% of the national production of this oilseed [1]. Soybean production in the Cerrado region is expected to continue to be an important driver of Brazilian grain production in the coming years or decades. However, Cerrado soils, mostly oxisols and deep sandy entisols, are acidic, dystrophic, and poor in many essential plant nutrients, such as potassium (K) [2–4], which has often limited the increase in soybean productivity in this region [5].

Therefore, the low fertility of Cerrado soils is the main cause of the gap between the low crop-grain yield and their productive potential, and the low K availability represents one of the most limiting factors for soybean development and productivity [6–8]. This low availability of K is even more limiting in sandy, sandy loam, and sandy clay loam soils, which are predominant in the Cerrado region, due to the high susceptibility of these soils to K losses by leaching [9,10]. Under these conditions, therefore, there is a need to enhance the use of natural resources available in agricultural production systems, especially regarding the sustainable use of soil K and potash fertilizers [10–12].

Soybeans have a high K requirement; on average, the rate of K extraction by the plants is around 42 to 48 kg of K for the production of one ton of grain [10,13]. Therefore, large quantities of K are required by soybean plants since this crop is highly sensitive to K deficiency [14], especially the modern high-yield soybean genotypes. Indeed, Esper-Neto et al. [13] reported that the amount of K removed by modern soybean genotypes was 21% to 45% higher compared with soybean genotypes historically planted in Brazil during the 20th century. The K deficiency limits plant development and the grain yield of soybeans by negatively affecting vital plant processes such as water status, cellular turgidity, protein synthesis, assimilate transport, cell expansion, and enzyme activation [15–17]. In turn, this high K requirement of the soybean crop contrasts with the normally insufficient K contents of tropical soils in the Cerrado region, which has increased the consumption of K fertilizers and production costs in recent years [18].

An alternative to improve K uptake and K fertilizer use consists of planting soybean genotypes that are K-use efficient or K-stress tolerant, which reduces the demand and expenditure on mineral fertilizers. Genotypic differences in K-use efficiency are related to plants' uptake, transport, and use of this nutrient. The ability of the root system to acquire large amounts of K from the soil and translocate this nutrient to the shoots of plants plays a key role in improving the K-use efficiency of soybean genotypes [19]. Therefore, the use of soybean genotypes with a vigorous root system capable of extracting large amounts of exchangeable K from the soil, or roots with a greater capacity to solubilize non-exchangeable K from the soil through the exudation of organic acids, is fundamental for the sustainability of Brazilian soybean production systems [6,13,20]. This fact has been even more relevant in recent years, because farmers use new soybean genotypes with greater productive potential each growing season, increasing the requirement and demand for soil K in Brazilian soybean fields [13].

The identification of modern high-yield soybean genotypes with greater K-use efficiency and greater response to K fertilization may be an economically viable alternative to enhance crop development and yield in Cerrado sandy soils with low K availability. However, knowledge about the K-use efficiency of modern soybean genotypes grown in Brazil remains limited, and information on the differential response of modern Brazilian genotypes to K fertilization is lacking. Therefore, this study was conducted to investigate the response of 25 modern high-yield soybean genotypes for K-use efficiency in a sandy soil of the Brazilian Cerrado.

2. Material and Methods

2.1. Study Description and Growth Conditions

The experiment was performed at Cassilândia, Mato Grosso do Sul, Brazil (19°05′29″ S and 51°48′50″ W, altitude 540 m), from November 2019 to February 2020, in 12 L pots, under greenhouse conditions. The minimum and maximum temperatures during the trial were 21.7 °C and 29.3 °C, respectively, and the average relative humidity was 78% (±6%).

The soil used in the trial was a K-deficient typical quartzipsamment (sandy entisol), collected from a Cerrado agricultural area, with 120 g kg^{-1} of clay and 840 g kg^{-1} of sand, pH 4.6, 7.8 mg dm^{-3} of P (Mehlich-1), 1.50 $cmol_c$ dm^{-3} of Ca^{2+}, 0.50 $cmol_c$ dm^{-3} of Mg^{2+}, 0.10 $cmol_c$ dm^{-3} of K^+, 5.70 $cmol_c$ dm^{-3} of CEC, 37% of soil base saturation, and 120 g dm^{-3} of organic carbon.

Soil active acidity was corrected using 1.11 g dm^{-3} of limestone (38% CaO and 11% MgO) to raise the soil base saturation to 70% [21]. Then, the soil was rinsed and maintained for 50 days with moisture content close to field capacity. After this period, the soil was transferred to 12 L plastic pots and fertilized with 15 mg N dm^{-3} (urea), 200 mg P dm^{-3} (simple superphosphate), 15 mg S dm^{-3} (gypsum), 3 mg Zn dm^{-3} (zinc sulfate), 2 mg Cu dm^{-3} (copper sulfate), and 1 B mg dm^{-3} (boric acid). The pots were filled with 10 dm^3 of soil sieved in a 5.0-mm mesh.

2.2. Experimental Design and Treatments

The treatments were distributed in a completely randomized design (CRD), using two K-fertilization levels [20 mg K dm^{-3} (low level) and 200 mg K dm^{-3} (high level)] and 25 modern soybean genotypes, in a factorial arrangement (2 × 25) with six replicates. Three replicates were collected at full flowering (R_3 stage) for evaluation of morphological traits, and the other three replicates were cultivated until the physiological maturity of the soybean to evaluate the components of production and grain yield. The K fertilizer used was potassium chloride (60% of K_2O).

2.3. Soybean Genotypes, Inoculation, and Experiment Conduction

Seeds from 25 modern high-yield soybean genotypes widely grown in the Brazilian Cerrado region (Table 1) were produced under field conditions at Cassilândia, MS, Brazil (19°05′45″ S, 51°48′52″ W, mean altitude 520 m) during the 2018/2019 harvest. The seeds were then stored in paper bags at 12–14 °C and 33–37% relative humidity until their use in this study.

Seeds were inoculated with *Bradyrhizobium japonicum* using the bioinoculant StarFix® (Lallemand Plant Care Inc., Patos de Minas, Brazil), containing SEMIA 5080 and SEMIA 5079 strains (minimum concentration of 1.0 × 10^{10} viable cells per mL) at a rate of 3.0 mL kg^{-1} of seeds. Seeds were then treated with molybdenum and cobalt using the commercial fertilizer Nodulus® PremiumTT (Vittia Fertilizers and Biologicals S.A., São Joaquim da Barra, Brazil), containing 15% Mo and 1.5% Co, at a rate of 2.0 mL kg^{-1} of seeds. Biological nitrogen fixation in soybean plants is enhanced when the seed is treated with Mo and Co prior to seeding [22].

Two plants from the 25 soybean genotypes were grown in individual pots and randomly distributed in the greenhouse. Soil moisture content was maintained close to the field capacity with daily irrigations using an automated micro-sprinkler system. The pest and disease control during the experiment was carried out according to need and the technical recommendations for the soybeans.

2.4. Leaf Sampling and K Analysis

At the R1 growth stage, leaf samples were collected from all pots. A newly expanded trifoliolate leaf from one of the four upper nodes was collected from all soybean plants grown in the pots. The trifoliolate leaves were placed in a labeled paper bag and oven-dried at 65 °C for 3 days. The dried leaves were ground in a Wiley mill to pass through a 1.0 mm sieve, digested with concentrated HNO_3 and 30% H_2O_2 [23], and analyzed for K concentration by flame photometry (PX-1381, Panomex Inc., New Delhi, India).

Table 1. Some of the agronomic characteristics of the modern high-yield soybean genotypes used in the analysis of K-use efficiency.

N°	Genotype	Agronomic Characteristics		
		Maturation Cycle †	RMG ††	Plant Growth Habit
G1	TMG2383 IPRO	120	8.3	Semideterminate
G2	TMG2381 IPRO	120	8.1	Indeterminate
G3	TMG2378 IPRO	125	7.8	Semideterminate
G4	TMG7067 IPRO	112	7.2	Semideterminate
G5	TMG7063 IPRO	110	7.0	Indeterminate
G6	TMG2165 IPRO	112	6.5	Indeterminate
G7	TMG 061 IPRO	110	6.1	Indeterminate
G8	97R50 IPRO	115	7.5	Indeterminate
G9	98R31 IPRO	130	8.3	Indeterminate
G10	98R35 IPRO	130	8.3	Indeterminate
G11	HO Cristalino IPRO	125	8.3	Indeterminate
G12	HO Maracaí IPRO	120	7.7	Indeterminate
G13	HO Paranaíba IPRO	115	7.4	Indeterminate
G14	BMX Foco IPRO	110	7.2	Indeterminate
G15	BMX Bônus IPRO	120	7,9	Indeterminate
G16	ST777 IPRO	108	7.7	Indeterminate
G17	ST797 IPRO	110	7.9	Indeterminate
G18	RK8115 IPRO	120	8.1	Indeterminate
G19	RK6719 IPRO	105	6.7	Indeterminate
G20	RK7518 IPRO	112	7.5	Indeterminate
G21	RK8317 IPRO	125	8.3	Indeterminate
G22	M5917I PRO	95	5.9	Indeterminate
G23	NS8399 IPRO	120	8.3	Indeterminate
G24	NS7007 IPRO	98	7.1	Indeterminate
G25	NS7505 IPRO	118	7.5	Indeterminate

† Soybean average maturation cycle (in days). †† RMG: Relative maturity group.

2.5. Quantification of Plant Morphological Traits

At the R3 growth stage, plant samples were collected to determine the following morphological traits: plant height (PH), leaf area (LA), stem diameter (SD), shoot dry matter (SDM), and root dry matter (RDM). Plants were divided into leaves, stems, and roots, oven-dried for three days at 65 °C and weighed. Leaf area (LA) was calculated using the following equation proposed by Richter et al. [24]: LA = [2.0185 × (L × W)], where L is the length of the central leaflet, and W is the maximum width of the central leaflet.

2.6. Quantification of Grain Yield and Production Components

At physiological maturity (R8 stage), the production components [final plant height (FPH), first pod insertion height (FPIH), pod number per plant (PNP), grain number per pod (GNP), and 1000-grain weight (1000-G)] and grain yield were determined. Grains were weighed, and grain yield (GY) was calculated after the correction of grain moisture content to 13%.

2.7. Calculation of K-Use Efficiency and Response to K Fertilization

The K-use efficiency (KUE) of each soybean genotype at each level of K fertilization (low or high K availability in the soil) was calculated according to Equation (1) proposed by Moll et al. [25]:

$$\mathrm{KUE_{ij}} = \mathrm{GY_{ij}}/\mathrm{K_j} \quad (1)$$

where $\mathrm{KUE_{ij}}$ is the K-use efficiency of the i-th genotype, with i ranging from 1 to 25, at the j-th K-fertilization level, with j ranging from 1 to 2 (i.e., low and high K availability); $\mathrm{GY_{ij}}$ is the grain yield of the i-th genotype at the j-th K-fertilization level; and, $\mathrm{K_j}$ is the K rate applied at the j-th fertilization level.

The response efficiency (RE) of soybean genotypes to K fertilization was calculated according to Equation (2), as proposed by Craswell and Godwin [26]:

$$ER_i = \Delta GY_i / \Delta KR \quad (2)$$

where ER_i is the response efficiency of the i-th genotype to K fertilization, with i ranging from 1 to 25; ΔGY_i is the difference in grain yield at the two K-fertilization levels (low and high K availability) for the i-th genotype; and ΔKR is the difference between the K rates applied in the two fertilization levels.

2.8. Statistical Analysis

All data were previously tested for normality of residues (Kolmogorov–Smirnov test; $p > 0.05$) and homoscedasticity of variances (Levene test; $p > 0.05$), and then, data were subjected to analysis of variance following the statistical model described below:

$$Y_{ijk} = \mu + G_i + K_j + G \times K_{ij} + e_{ijk} \quad (3)$$

where Y_{ijk} is the value of the dependent variable assessed in the i-th genotype and j-th K-fertilization level; μ is the overall mean of the tests; G_i is the effect of the i-th genotype; K_j is the effect of the j-th K-fertilization level; $G \times Eij$ is the random effect of the interaction between i-th genotype and j-th K-fertilization level; e_{ijk} is the random error associated with the dependent variable (Y_{ijk}). The difference between each K-fertilization level was demonstrated using a box plot for each dependent variable (plant morphological traits, production components, and grain yield).

Genotype classification according to K-use efficiency and response to K fertilization was carried out using the method proposed by Fageria and Kluthcouski [19]. This method, through a graphical representation in the Cartesian plane, allows the identification of suitable genotypes for each production environment condition. In the Cartesian plane, the abscissa axis (x) represents the K-use efficiency (i.e., the average grain yield of genotypes grown under low K availability), whereas the ordinate axis (y) represents the response efficiency (RE) to K fertilization. The average value of the K-use efficiency and the response to K fertilization represents the axes' origin point. In this method, therefore, soybean genotypes were divided into four groups: efficient and responsive genotypes (ER); inefficient and responsive genotypes (IR); inefficient and non-responsive genotypes (INR); and efficient and non-responsive genotypes (ENR).

Hierarchical cluster analysis (HCA) of 25 soybean genotypes based on standardized mean Euclidean distance (D) and Ward's hierarchical minimum variance method was performed using all morphological traits, yield components, and grain yield of the crop [27]. The 40% similarity value was used as a criterion to separate groups of genotypes efficient in K use or genotypes responsive to the K fertilizer application at each potash fertilization level (low or high K availability). According to Cargnelutti-Filho et al. [28], similarity values between 40% and 50% can be used as a criterion to separate groups of genetic materials.

3. Results and Discussion

The analysis of variance reported significant effects ($p \leq 0.05$) of the interaction between soybean genotypes and levels of K fertilization for all plant morphological characteristics except for stem diameter and first pod insertion height (Table 2). This significant effect of the interaction between genotypes and K level indicates that soybean genotypes have distinct responses when grown under conditions of low or high K availability in the soil.

Table 2. Summary of variance analysis of the effects of genotypes and K-fertilization levels on morphological traits, leaf K concentration, production components, and soybean grain yield [*Glycine max* (L.) Merrill.] grown in a Brazilian Cerrado sandy soil.

Causes of Variation	**Probability > F**						
	PH	**SD**	**LA**	**SDM**	**RDM**	**TDM**	**K**
Genotype (G)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Potassium level (K)	<0.001	0.082	<0.001	<0.001	0.496	<0.001	<0.001
Interaction G × K	0.003	0.124	0.001	0.004	<0.001	<0.001	<0.001
Overall average	64.0	10.2	18.1	23.8	17.9	41.7	20.9
CV (%)	5.17	8.73	9.31	8.70	12.92	8.40	12.45
Causes of variation	**Probability > F**						
	KUE	**FPH**	**FPIH**	**PNP**	**GNP**	**1000-G**	**GY**
Genotype (G)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Potassium level (K)	<0.001	0.018	0.154	<0.001	0.034	0.016	<0.001
Interaction G × K	<0.001	0.045	0.243	<0.001	0.041	0.038	<0.001
Overall average	58.7	72.0	14.7	34.3	2.08	186.0	26.3
CV (%)	12.87	8.46	12.35	9.87	7.62	10.47	12.53

PH: plant height. SD: stem diameter. LA: leaf area. SDM: shoot dry matter. RDM: root dry matter. TDM: total dry matter. K: potassium concentration in the leaves. KUE: potassium-use efficiency. FPH: final plant height. FPIH: first pod insertion height. PNP: pod number per plant. GNP: grain number per pod. 1000-G: 1000-grain weight. GY: grain yield. CV: coefficient of variation.

The application of a high level of K fertilizer resulted in the highest value for most morphological characteristics of soybean plants, except for stem diameter and root dry matter (Figure 1). These results show the importance of adequate management of K fertilization, especially about the amount of K to be applied to the soybean crop. The greater growth and development of soybean plants with the application of high K levels is associated with the low exchangeable K content of the soil used in this experiment (0.10 $cmol_c$ dm^{-3} of K). Cerrado tropical soils, especially sandy soils, are known to have low K availability [6,7], caused by the high degree of weathering and high leaching rate of this nutrient [9,10]. These conditions determine the agricultural potential of tropical sandy soils, which have low water retention capacity, low cation-exchange capacity (CEC), and low particle aggregation capacity caused by low clay content (<15%) and low organic matter content [29]. Therefore, under these conditions, the rational use of K fertilization is very important for the agricultural exploitation of these soils.

Plant height (Figure 1A), leaf area (Figure 1C), and shoot dry matter (Figure 1D) were the morphological characteristics of soybean plants most impacted by the levels of applied K fertilizer. Steiner et al. [17] also reported that the application of a high level of K fertilizer increased plant height, leaf area, and shoot dry matter of the soybean crop [18]. Potassium activates numerous enzymes important for photosynthesis, protein synthesis, nitrogen and carbon metabolism, and sugar transport [16]. Potassium is also crucial in cell growth, an important metabolic process for plant function and development [14,16]. Therefore, K plays an important role in soybean plants' growth and physiological metabolism. Soil K deficiency limits the growth of soybean plants by causing adverse effects on plant metabolism, resulting in lower leaf water content, cell expansion, osmotic regulation, carbohydrate and protein synthesis, and lower transport of photoassimilates [15–17].

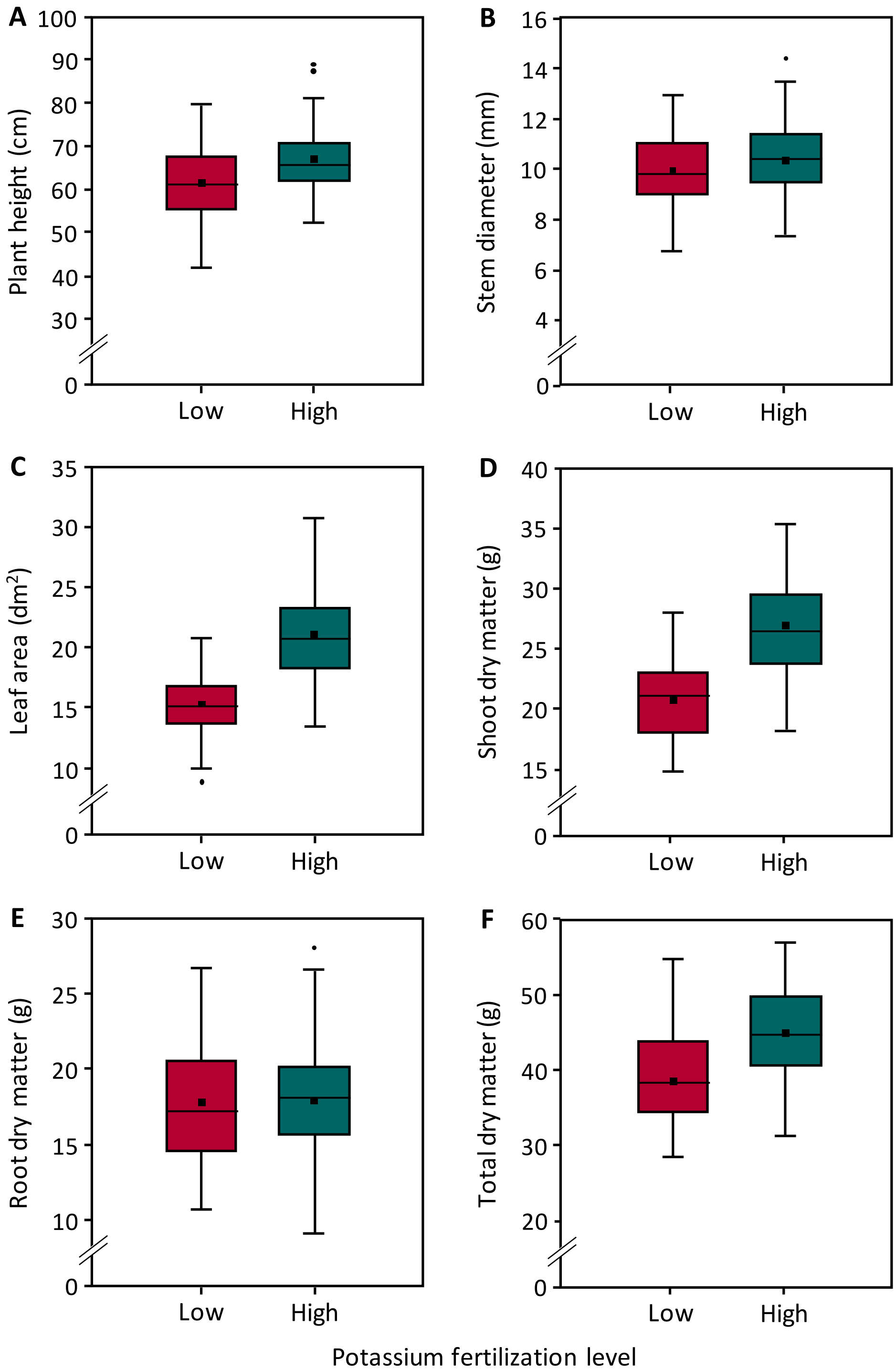

Figure 1. Boxplot of the effect of K fertilization (low and high) on plant height (**A**), stem diameter (**B**), leaf area (**C**), shoot dry matter (**D**), root dry matter (**E**), and total dry matter (**F**) for the 25 modern soybean genotypes [*Glycine max* (L.) Merrill.] grown on Brazilian Cerrado sandy soil. • is an outlier. ■ is the overall average. The total number of samples (n) for each level of K fertilizer was 75.

Levels of potassium fertilization significantly affected the final plant height, pod number per plant, 1000-grain weight, and grain yield of soybeans (Figure 2). The pod number per plant, 1000-grain weight, and grain yield were the most limited production components under conditions of low K availability (Figure 2C,E,F). Plants exposed to nutritional stress conditions, such as low K availability in the soil, can express a series of morphological and physiological changes, which include increased abscission of pods mainly caused by loss of leaf turgor [17]. Therefore, the application of a high level of K may have improved the osmolyte synthesis of the plants, resulting in higher leaf water content and greater regulation of osmotic adjustment [30,31], which reduced the abscission of plant pods.

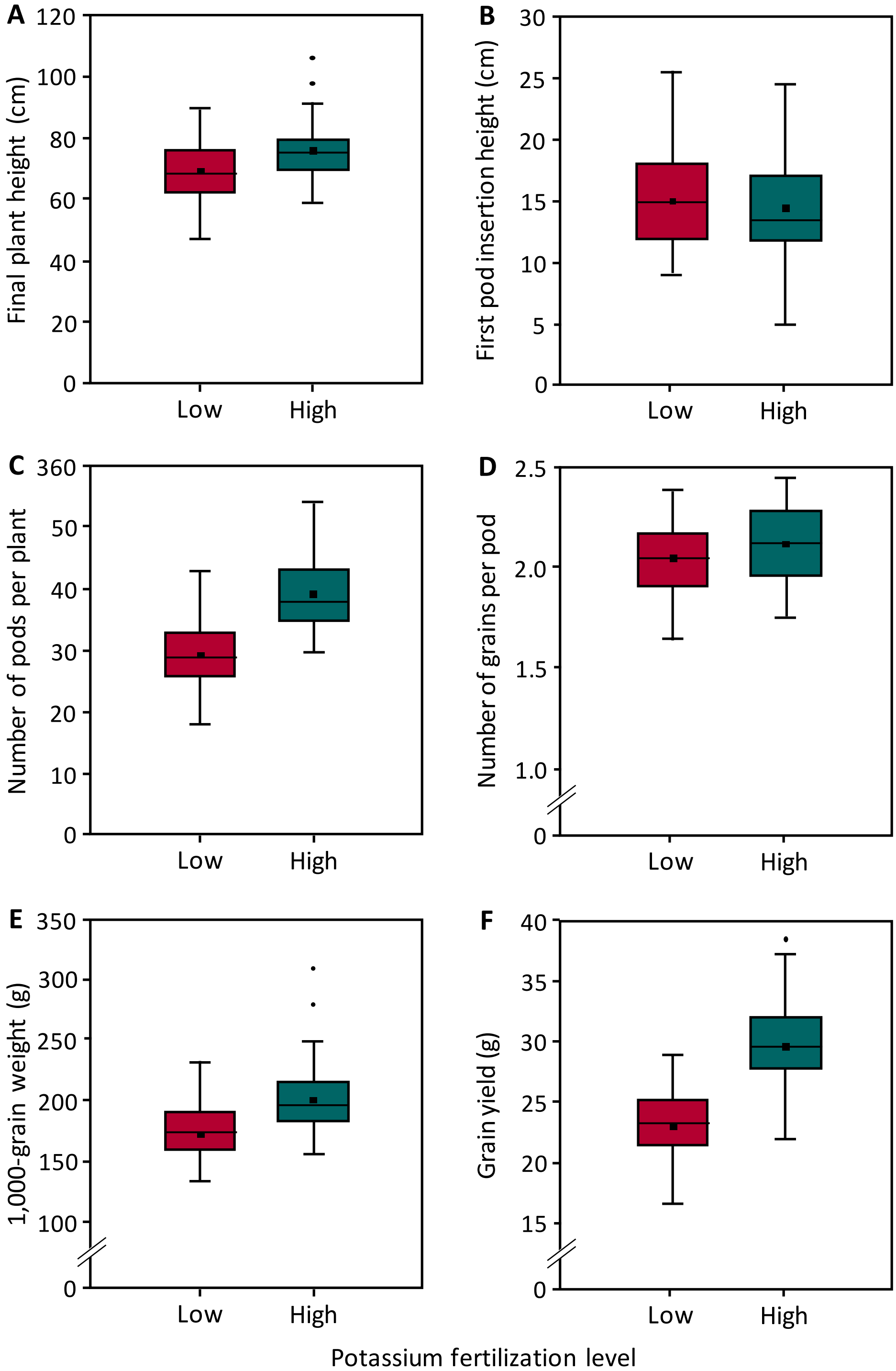

Figure 2. Boxplot of the effect of K fertilization (low and high) on final plant height (**A**), first pod insertion height (**B**), pod number per plant (**C**), grain number per pod (**D**), 1000-grain weight (**E**), and grain yield (**F**) for the 25 modern soybean genotypes [*Glycine max* (L.) Merrill.] grown on Brazilian Cerrado sandy soil. • is an outlier. ■ is the overall average. The total number of samples (n) for each level of K fertilizer was 75.

The greater 1000-grain weight and grain yield with the application of a high level of K fertilizer is associated with the fact that this fertilization increased the availability of this nutrient in the soil and the K concentration in the leaves of the soybeans. Studies have reported the importance of this nutrient for plant development and grain size [32,33]. Low soil K availability may result in lower growth and development of soybean plants, fewer pods per plant, and smaller grain size, and these characteristics affect soybean grain yield [17,31]. Therefore, the application of high K levels may have improved the translocation of this nutrient from the leaves to the pods during the grain-filling phase, increasing weight and grain yield.

Leaf K concentration under conditions of low K availability ranged from 9.8 to 16.2 g kg^{-1}, with an average content of 12.8 g kg^{-1} (Figure 3A). The absorption of K by soybean plants with the application of a low level of K fertilizer shows that the concentration of this nutrient in the leaf tissue was below the range considered appropriate for the crop. According to Malavolta et al. [23], the appropriate K concentration range for soybeans is between 17 and 25 g kg^{-1}. However, under conditions of high K availability, leaf K concentration ranged from 25.0 to 32.7 g kg^{-1}, with an average value of 29.1 g kg^{-1} (Figure 3A). These values indicate that the K concentration in soybean leaf tissue was just above the upper level considered adequate for the crop.

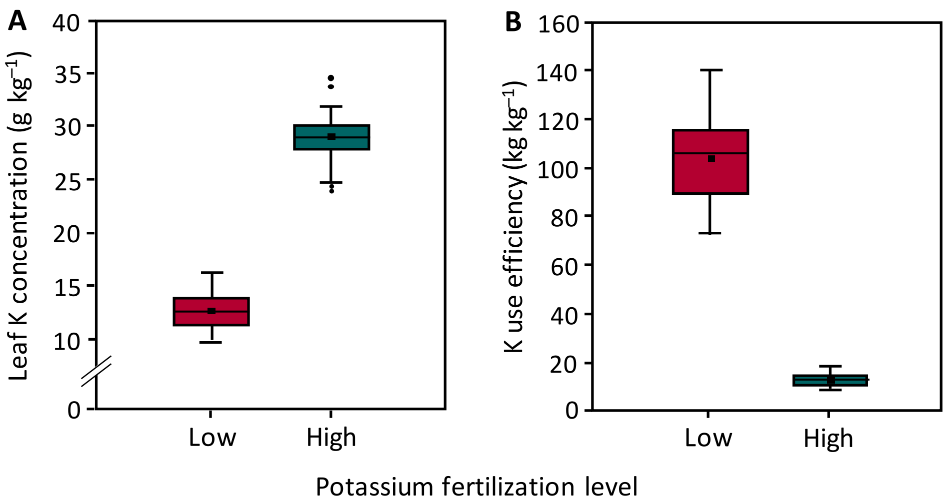

Figure 3. Boxplot of the effect of K fertilization (low and high) on leaf K content (**A**) and K-use efficiency (**B**) for the 25 modern soybean genotypes [*Glycine max* (L.) Merrill.] grown on Brazilian Cerrado sandy soil. • is an outlier. ■ is the overall average. The total number of samples (n) for each level of K fertilizer was 75.

The increase in foliar K concentration of plants with the application of a high level of K fertilization reflects the greater availability of this nutrient in the soil. In addition, under conditions of high availability of K in the soil, plants can absorb amounts of K greater than their metabolic requirement, which is accumulated in cellular organelles (such as chloroplasts, mitochondria, and especially vacuoles), characterizing "luxury consumption" [34]. The increase in leaf K concentration with the application of high levels of potassium fertilization has frequently been reported in other studies [35,36].

The K-use efficiency ranged from 73 to 140 kg kg^{-1} and 9 to 18 kg kg^{-1} under conditions of low and high soil K availability, respectively (Figure 3B). The lower K-use efficiency with the application of a high level of potassium fertilizer is related to Mitscherlich's law of diminishing returns. Mitscherlich's law of diminishing returns reports that when increasing rates of a nutrient are added, the highest productivity increment is obtained with the lowest applied rate, and with successive applications of the nutrient, the productivity increments and the nutrient-use efficiency will be gradually smaller [23]. Therefore, the application of

K fertilizer at the highest rate (200 mg K dm^{-3}) resulted in lower K-use efficiency when compared with the lowest rate of potassium fertilizer (20 mg K dm^{-3}).

The response efficiency of soybean genotypes to K fertilization ranged from 0.97 to 5.50 kg kg^{-1}, with a mean response efficiency value of 3.35 kg kg^{-1} (Figure 4). The highest responses to K fertilization were obtained for genotypes "TMG 2381 IPRO", "98R35 IPRO", "HO Maracaí IPRO", "BMX Bônus IPRO", "RK 8115 IPRO", and "RK7518 IPRO", followed by soybean genotypes "TMG2383 IPRO", "TMG7063 IPRO", "98R31 IPRO", "BMX Foco IPRO", "ST797 IPRO", and "M5917 IPRO", while the lowest responses to K fertilization response were obtained for genotypes "97R50 IPRO", "HO Paranaíba IPRO", and "NS7505 IPRO" (Figure 4).

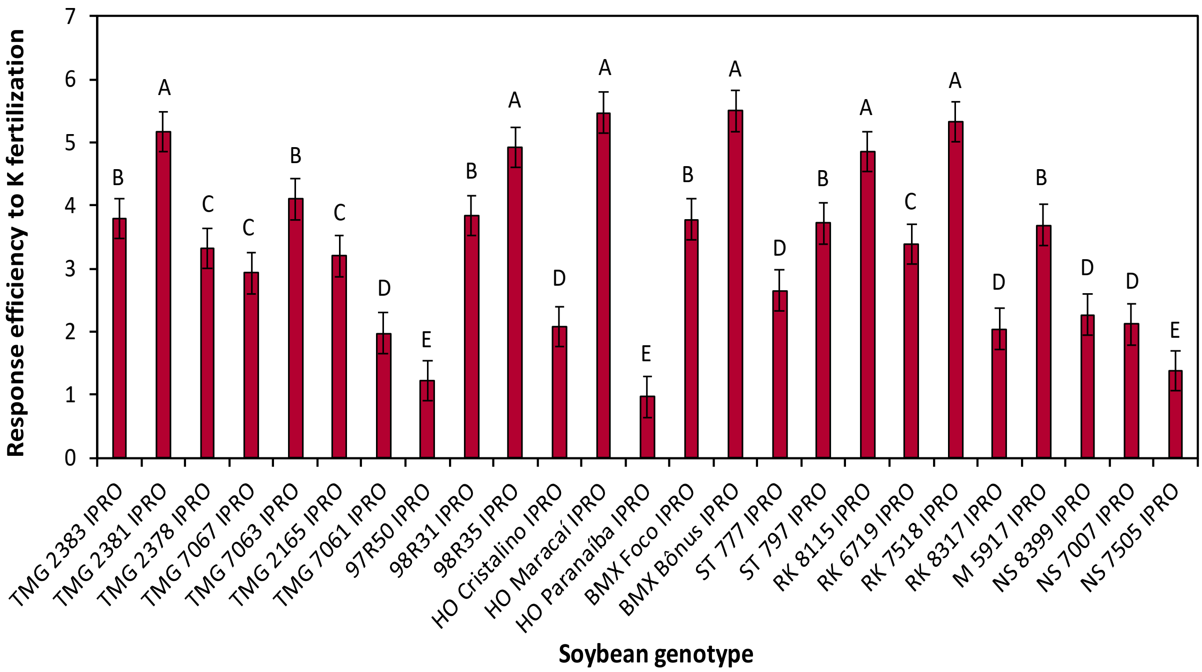

Figure 4. Response efficiency to K fertilization of 25 soybean genotypes [*Glycine max* (L.) Merrill.] grown on Brazilian Cerrado sandy soil. Bars followed by distinct letters are different according to the Scott–Knott test at the 5% probability level.

The classification of soybean genotypes for K-use efficiency and K fertilization response was determined by the method proposed by Fageria and Kluthcouski [19] and by multivariate analysis of hierarchical clustering. Based on the Fageria and Kluthcouski method, 13 soybean genotypes were classified as efficient in the use of soil K, as they had a grain yield greater than the average value of all genotypes when grown in conditions of low K availability. These genotypes are represented in Group 1 and Group 2 in Figure 5. The use of genotypes efficient in the absorption and use of K is important to enhance the yield of soybeans when the crop is grown in sandy soils of the Cerrado region with low availability of K. On the other hand, 12 soybean genotypes were classified as responsive to potassium fertilization, as they had grain yields higher than the average of all genotypes when grown under high soil K availability. These soybean genotypes are represented in Group 1 and Group 2 in Figure 5. Some studies have reported the existence of genetic variability between genotypes for absorption capacity and K-use efficiency [37,38].

The soybean genotypes "TMG2381 IPRO", "TMG7063 IPRO", "BMX Bônus IPRO", and "ST797 IPRO" were classified as efficient in K use and responsive to K fertilization (Figure 5). These genotypes had grain yields higher than the average of all genotypes under low and high soil K availability. Soybean genotypes belonging to this group can be recommended for cultivation in soils with low K availability or in agricultural areas that will be fertilized with high rates of potassium fertilizers.

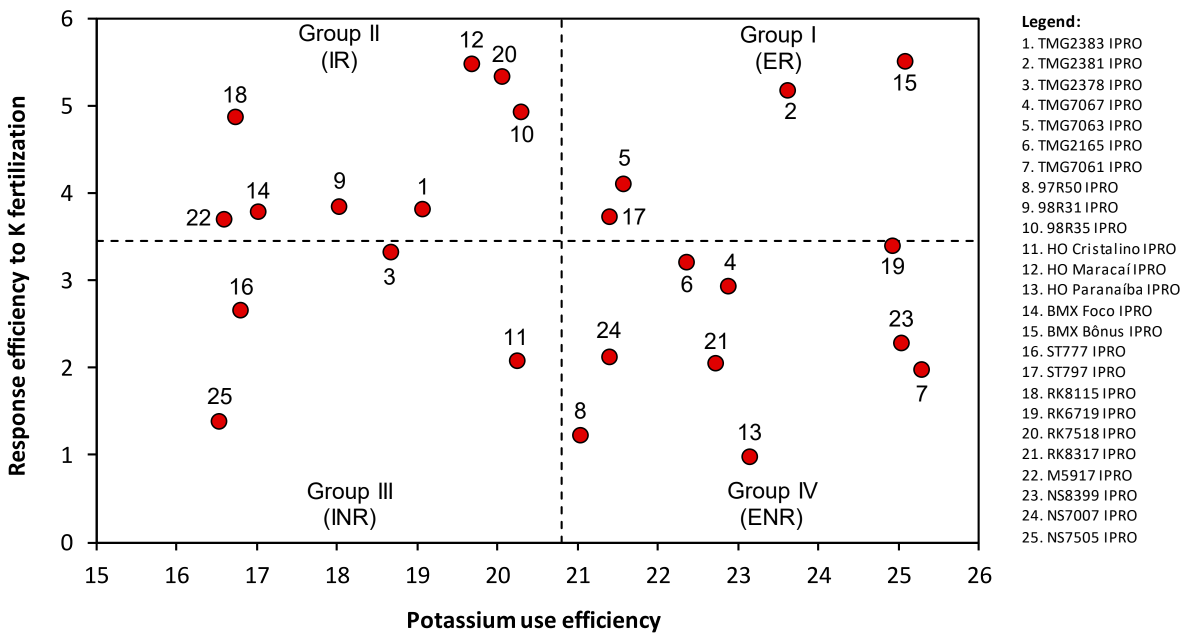

Figure 5. Classification of 25 modern high-yield soybean genotypes [*Glycine max* (L.) Merrill.] into four categories for K-use efficiency and response to K fertilization when grown on Brazilian Cerrado sandy soil. (ER: efficient and responsive; IR: inefficient and responsive; INR: inefficient and non-responsive; ENR: efficient and non-responsive).

The soybean genotypes "TMG2383 IPRO", "98R31 IPRO", "98R35 IPRO", "HO Maracaí IPRO", "BMX Foco IPRO", "RK8115 IPRO", "RK7518 IPRO", and "M5917 IPRO" were classified as inefficient and responsive to K fertilization (Figure 5). These genotypes had grain yields below the average of all genotypes when grown under low K availability in the soil; however, when the genotypes were fertilized with a high level of K they had a positive grain yield response above average when compared with all genotypes (Figure 5). These inefficient and responsive genotypes are suggested for cultivation by farmers who use a high level of K fertilization.

The soybean genotypes "TMG2378 IPRO", "HO Cristalino IPRO", "ST777 IPRO", and "NS7505 IPRO" were classified as inefficient and unresponsive to K fertilization. These genotypes have grain yields below the average of all genotypes when grown under low or high K availability (Figure 5). The genotypes classified as inefficient and non-responsive are not suitable to be cultivated in sandy Cerrado soils, regardless of the use of high or low rates of K fertilizer.

The genotypes "TMG7067 IPRO", "TMG2165 IPRO", "TMG7061 IPRO", "97R50 IPRO", "HO Paranaíba IPRO", "RK6719 IPRO", "NS8399 IPRO", and "NS7007 IPRO" were classified as efficient and non-responsive to K fertilization (Figure 5). These soybean genotypes have grain yields above the average of all genotypes under low soil K availability; however, these genotypes have responses to K fertilization below the general average of all genotypes with the application of high rates of K fertilizer. These results show the low response of these soybean genotypes to the increase in soil K availability. Efficient and non-responsive soybean genotypes should be recommended for cultivation in agricultural areas with low soil K availability or in situations where conditions require farmers to apply low levels of K fertilization.

The classification of soybean genotypes efficient in K use and responsive to K fertilization was also carried out using the multivariate analysis method, considering all morphological characteristics and production components of the crop. The soybean genotypes were divided into three groups based on the standardized mean Euclidean distance (D), Ward's method, and the 40% similarity value (Figure 6). Under low soil K availability, the genotypes were classified as efficient, stable, or inefficient in K use (Figure 6A), while under high soil K availability, the genotypes were classified as responsive, stable, or non-responsive to K fertilization (Figure 6B).

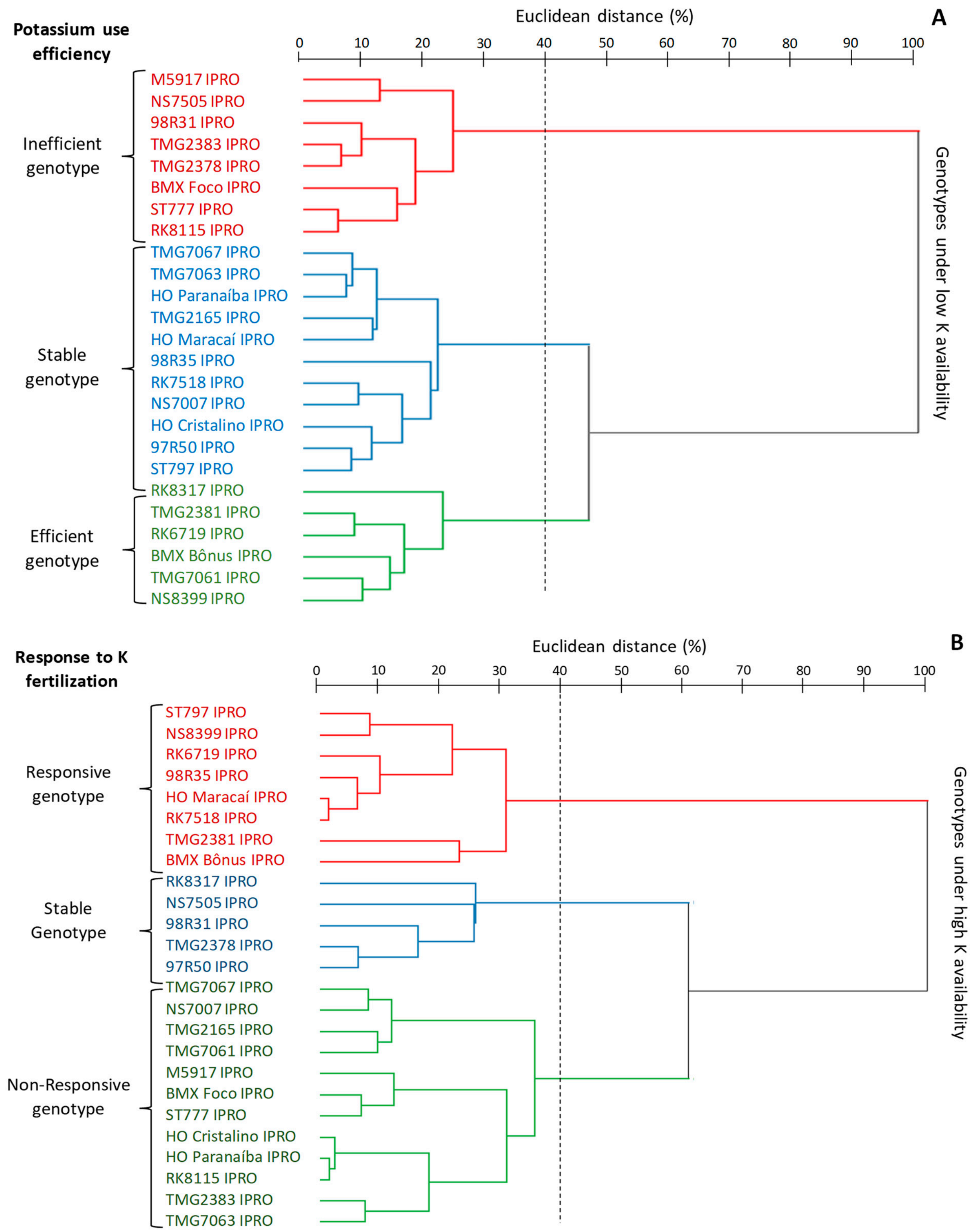

Figure 6. Dendrogram using standardized Euclidean distance and Ward's minimum variance method from the hierarchical cluster analysis (HCA) of 25 modern soybean genotypes [*Glycine max* (L.) Merrill.] under low (**A**) and high (**B**) soil K availability based on all plant morphological characteristics (PH, SD, LA, SDM, RDM, and TDM) and yield components (FPH, FPIH, PNP, GNP, 1000-G, and GY).

Under conditions of low soil K availability, the genotypes "M5917 IPRO", "NS7505 IPRO", "98R31 IPRO", "TMG2383 IPRO", "TMG2378 IPRO", "BMX Foco IPRO", "ST777 IPRO", and "RK8115 IPRO" were classified as inefficient in the use of soil K (Figure 6A). The genotypes in this group showed inferior performance in low soil K availability conditions and had the lowest values for most morphological traits and crop production components.

The genotypes "TMG7067 IPRO", "TMG7063 IPRO", "HO Paranaíba IPRO", "TMG2165 IPRO", "HO Maracaí IPRO", "98R35 IPRO", "RK7518 IPRO", "NS 7007 IPRO", "HO Cristalino IPRO", "97R50 IPRO", and "ST797 IPRO" have intermediate values for most morphological traits and crop production components and were classified as stable with intermediate efficiency under conditions of low soil K availability. On the other hand, the genotypes "RK8317 IPRO", "TMG2381 IPRO", "RK6719 IPRO", "BMX Bônus IPRO", "TMG7061 IPRO", and "NS8399 IPRO" showed the highest values for most morphological traits and crop production components and, therefore, were classified as efficient in their soil K use (Figure 6A). Under conditions of low soil K availability, the genotypes "ST797 IPRO", "NS8399 IPRO", "RK6719 IPRO", "98R35 IPRO", "HO Maracaí IPRO", "RK7518 IPRO", "TMG2381 IPRO", and "BMX Bônus IPRO" were classified as responsive to potassium fertilization. These genotypes showed the highest values for most morphological traits and production components of the soybean crop (Figure 6B).

On the other hand, the genotypes "TMG7067 IPRO", "NS7007 IPRO", "TMG2165 IPRO", "TMG7061 IPRO", "M5917 IPRO", "BMX Foco IPRO", "ST777 IPRO", "HO Cristalino IPRO", "HO Paranaíba IPRO", "RK8115 IPRO", "TMG2383 IPRO", and "TMG7063 IPRO" were classified as non-responsive to K fertilization, since these genotypes had the lowest values for most of the morphological traits and production components of the soybean crop when cultivated with the application of high levels of K fertilizer (Figure 6B).

In summary, the two methods used in this study (Fageria and Kluthcouski method and hierarchical cluster analysis) classified the genotypes "TMG7061 IPRO", "BMX Bônus IPRO", "RK6719 IPRO", and "RK8317 IPRO" as efficient in the use of soil K, and these are the most suitable soybean genotypes to be cultivated in agricultural soils with low K availability (Figures 5 and 6A). On the other hand, the soybean genotypes "98R35 IPRO", "HO Maracaí IPRO", "BMX Bônus IPRO", and "RK7518 IPRO" were classified as responsive to K fertilization, and are the most suitable soybean genotypes to be cultivated in agricultural areas with the application of high rates of K fertilizers (Figures 5 and 6A).

The soybean genotypes with the least dissimilarity under conditions of low soil K availability were "TMG2383 IPRO" × "TMG2378 IPRO", "ST777 IPRO" × "RK8115 IPRO", "TMG7063 IPRO" × "HO Paranaíba IPRO", and "97R50 IPRO" × "ST797 IPRO" (Figure 6A). Under conditions of high soil K availability, the soybean cultivars with the least dissimilarity were "HO Maracaí IPRO" × "RK7518 IPRO" and "HO Paranaíba IPRO" × "RK8115 IPRO" (Figure 6B). The greater similarity between these soybean genotypes indicates that genetic crossing between these genotypes should not be used because the genetic gain will be small or null.

4. Conclusions

The soybean genotypes "TMG7061 IPRO", "BMX Bônus IPRO", "RK6719 IPRO", and "RK8317 IPRO" were classified as efficient in the use of soil K and are the most suitable genotypes to be cultivated in agricultural soils with low K availability.

The genotypes "98R35 IPRO", "HO Maracaí IPRO", "BMX Bônus IPRO", and "RK7518 IPRO" were classified as responsive to K fertilization and are the most recommended genotypes for cultivation in agricultural areas with the application of high rates of K fertilizer.

The "BMX Bônus IPRO" genotype simultaneously combines characteristics of K-use efficiency and response to K fertilization. Therefore, this soybean genotype can be grown under conditions of low or high soil K availability. Furthermore, from the point of view of plant breeding, this genotype can be used as a parent in soybean crossing blocks to obtain efficient and K-fertilization responsive genotypes.

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