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Efficiency of phosphorus use by melon genotypes[1]

Eficiência de uso de fósforo por genótipos de meloeiro

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HIGHLIGHTS:

The plant characteristic that most contribute to the divergence between the genotypes is main branch length.
Under phosphorus restriction, the unimproved genotypes show greater efficiency of use and internal use of this nutrient.
The genotypes A-16, A-29, A-50, A-52 and 'Trinity' are efficient and responsive in the phosphorus restriction condition.

ABSTRACT: This study aimed to evaluate the efficiency of phosphorus use with melon genotypes cultivated in a hydroponic system. Ten melon genotypes were evaluated in solutions with and without phosphorus restriction. A randomized block design in a 10 × 2 factorial scheme was used, with five replicates. The following characteristics were evaluated: leaf number, stem diameter, main branch length, root system length, root system volume, chlorophyll, root and shoot phosphorus concentration ratio, total phosphorus, root and shoot dry matter ratio, total dry matter, and phosphorus use, acquisition, and internal utilization efficiencies. The existence of variability among genotypes was verified for all evaluated characteristics, except for chlorophyll. Genotypes A-16, A-29, A-50, A-52, and Trinity were classified as efficient and responsive in the phosphorus-restricted solution and are promising for breeding studies.

Key words: *Cucumis melo* L., phosphorus acquisition, plant breeding, plant nutrition, phosphorus response

RESUMO: Esta pesquisa objetivou avaliar a eficiência de uso de fósforo em genótipos de meloeiro cultivados em sistema hidropônico. Foram avaliados 10 genótipos de meloeiro em soluções nutritivas com e sem restrição de fósforo. Utilizou-se o delineamento em blocos casualizados no esquema fatorial 10 × 2, com cinco repetições. Foram avaliados os seguintes caracteres: número de folhas, diâmetro do caule, comprimento do ramo principal, comprimento do sistema radicular, volume do sistema radicular, clorofila, razão do teor de fósforo na raiz e parte aérea, fósforo total, razão da matéria seca na raiz e parte aérea, matéria seca total e eficiências de uso, de aquisição e de utilização interna de fósforo. Verificou-se a existência de variabilidade entre os genótipos para todos os caracteres avaliados, exceto para clorofila. Os genótipos A-16, A-29, A-50, A-52 e Trinity foram classificados como eficientes e responsivos na solução com restrição de fósforo, sendo promissores para estudos em melhoramento genético.

Palavras-chave: *Cucumis melo* L., aquisição de fósforo, melhoramento vegetal, nutrição de plantas, resposta ao fósforo

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INTRODUCTION

Melon (*Cucumis melo* L.) is a vegetable belonging to the Cucurbitaceae family that has a high commercial value worldwide (Sanabria-Verón et al., 2019). The Northeast region of Brazil is the largest producer and exporter of this fruit because of its favorable edaphoclimatic conditions and the use of advanced technology applied by the productive sector. Additionally, it is important for generating employment and income (Cavalcante Neto et al., 2020).

The melon crop requires a large amount of nutrients, and the lack of adequate phosphorus (P) supply most limits production (Li et al., 2018). This macronutrient is essential for melon development because it plays an important structural and regulatory role in photosynthesis, energy conservation, carbon metabolism, enzymatic reactions, and nucleic acid synthesis (Shen et al., 2011). Small amounts of P are available to plant roots by natural weathering processes, but the lack of sufficient P in soils is considered a limiting factor for melon development (Li et al., 2018; Dixon et al., 2020). To overcome this limitation, large amounts of phosphate fertilizers are applied to maintain agricultural production, contributing to increased production costs and a reduction in the use of non-renewable natural resources (Sattari et al., 2012).

In this context, several researchers have sought to identify varieties with more efficient P usage in different cultures (Uzokwe et al., 2017; Bilal et al., 2018; Bernardino et al., 2019; Li et al., 2020), either under field conditions or in a hydroponic system. Nevertheless, information on the efficiency of P use in melon germplasms remains scarce (Li et al., 2018). In addition, there are no efficiency records for modern hybrids and accessions used by growers in semi-arid conditions in Brazil.

The objective of this study was to evaluate the efficiency of phosphorus use by melon genotypes under a hydroponic system.

MATERIAL AND METHODS

The experiment was conducted in April 2019 in a greenhouse (covered with a net for 50% irradiation) belonging to the Centro de Ciências Agrárias (CCA) of the Universidade Federal Rural do Semi-Árido (UFERSA), in the municipality of Mossoró-RN, located at 5°12’48” S and 37°18’44” W, with an altitude of 37 m. During the experiment, the average temperature and relative humidity inside the greenhouse were 29.9 °C and 75%, respectively.

Ten melon genotypes were evaluated, five of which were improved (Vereda, Gaúcho Redondo Conesul (GRC), Amarillo Canário (Aca), Gaúcho Casca de Carvalho (GCC), and Trinity), and five were not improved (A-02, A-16, A-29, A-50, and A-52).

Sowing was conducted in polyethylene trays containing 200 cells filled with the commercial coconut fiber substrate Golden Mix Mixed 98® (total porosity: 94%; aeration capacity: 35%; available water holding capacity: 41%; pH: 5.1; electrical conductivity: 1.0 dS m^{-1}; N-nitrate: 8.1 mg dm^{-3}; phosphorus: 53.0 mg dm^{-3}; chloride: 44.6 mg dm^{-3}; sulfur: 92.1 mg dm^{-3}; N-ammonia: 17.7 mg dm^{-3}; potassium: 270.1 mg dm^{-3}; sodium: 12.6 mg dm^{-3}; calcium: 9.9 mg dm^{-3}; magnesium: 6.6 mg dm^{-3}; boron: 0.5 mg dm^{-3}; copper: 0.1 mg dm^{-3}; iron: 0.4 mg dm^{-3}; manganese: 0.1 mg dm^{-3}; and zinc: 0.5 mg dm^{-3}) (Amafibra, 2022).

A randomized block design with five replicates was used, and the experimental unit was represented by a plastic pot (10 L). A 10 × 2 factorial scheme was employed, with 10 melon genotypes and two nutrient solutions (P+: solution without phosphorus restriction; P-: solution with phosphorus restriction), totaling 20 treatments.

The experiment was performed in a floating hydroponic system called the deep film technique (DFT), and the experimental unit was represented by a plastic pot with a capacity of 10 L (24 cm high, 18 cm lower diameter, and 23 cm upper diameter) containing 8 L of nutrient solution.

The seedlings were transplanted 15 days after sowing when they had a pair of permanent leaves, with one seedling per pot. A 10 mm thick and 21 cm diameter expanded polystyrene disk was placed in each pot. in the center of each disk, a hole with a diameter of 4.5 cm was made, where a plastic cup with a capacity of 80 mL was placed. Two rectangular openings were made at the base of each plastic cup to allow the roots to pass through (Martinez, 2021).

Oxygenation of the nutrient solution occurred continuously using an air compressor (model ACO-008 120 W 220 v) at a flow rate of 110 L min^{-1}. The air distribution system in the pots consisted of microtubes with a 0.5 mm internal diameter and PVC connections.

The nutrient solution was prepared using water with the following composition (mg L^{-1}): 152 N, 39 P, 245 K, 119 Ca, 29 Mg, and 32 S (Castellane & Araújo, 1994). The micronutrients were supplied using Rexolin® (30 mg L^{-1}), with the following concentration: 11.60% potassium oxide, 1.28% sulfur, 0.86% magnesium, 2.10% boron, 2.66% iron, 0.36% copper, 2.48% manganese, 0.04% molybdenum and 3.38% zinc. The nutrient phosphorus-restricted solution (P) had the same concentration of nutrients, except for P, for which only the amount present in the water used in the preparation of the nutrient solution was available.

To quantify the phosphorus concentration in water, a physicochemical analysis was performed in triplicate using the methodology prescribed in the Standard Methods for the Examination of Water and Wastewater (APHA, 2017).

The following fertilizers were used during the preparation of nutrient solutions: calcium nitrate ($CaNO_3$: 16% N and 27% CaO), potassium nitrate (KNO_3: 13% N and 45% K_2O), potassium chloride (KCl: 60% K_2O), monoammonium phosphate (MAP: 11% N and 61% P_2O_5), and magnesium sulfate ($MgSO_4$: 9% Mg and 11% S). Due to the use of MAP in the standard nutrient solution, sodium nitrate ($NaNO_3$) was used for proportional replacement of N in the P-restricted solution. Daily monitoring of the nutrient solution was carried out to control electrical conductivity and pH.

At the end of the experiment (19 days after transplantation), the following characteristics were evaluated: leaf number (NL), stem diameter (SD), main branch length (MBL), root system length (RSL), root system volume (RSV), relative chlorophyll index (RCI), total dry mass (TDM), and root to shoot dry mass ratio [$DM_{(R/S)}$].

The P concentration in the plants was quantified by spectrophotometry with molybdenum blue (Meneghetti, 2018). The root/shoot ratio was calculated from the P concentrations identified in the shoots and roots.

Based on the biomass accumulation and P concentration in the plant tissue, the following efficiency indexes were determined according to the methodology of Moll et al. (1982): phosphorus use efficiency (PUE), phosphorus acquisition efficiency (PAE), and phosphorus internal use efficiency (PIUE). These indexes were obtained using Eqs. 1, 2, and 3, respectively.

$$\text{PUE} = \frac{\text{DM}(\text{g})}{\text{P}_{\text{applicated}}(\text{g})} \tag{1}$$

$$\text{PAE} = \frac{\text{P}_{\text{accumulated}}(\text{g})}{\text{P}_{\text{applicated}}(\text{g})} \tag{2}$$

$$\text{PIUE} = \frac{\text{DM}(\text{g})}{\text{P}_{\text{accumulated}}(\text{g})} \tag{3}$$

For normally distributed characteristics, univariate and multivariate analyses of variance were performed using the F-test and Wilks criterion at $p < 0.01$ respectively. Averages were grouped according to the methodology proposed by Scott and Knott. Analyses were performed using Genes software version 1990.2019.89 (Cruz, 2013).

Genetic dissimilarity among genotypes was estimated using the standardized Euclidean distance. The genotypes were hierarchically grouped using the average distance between groups method, UPGMA. The graphical representation was validated using the cophenetic correlation coefficient. The relative contribution of quantitative characteristics to genetic divergence was estimated (Singh, 1981). The selection index of each genotype and its classification as efficient and responsive to phosphorus were obtained, as described by Parentoni et al. (2011). Cluster analyses were performed using the cluster package implemented in R (R Core Team, 2021).

RESULTS AND DISCUSSION

Phosphorous restriction (P-) considerably affected plant growth in all genotypes, showing a reduced leaf number (NL), stem diameter (SD), main branch length (MBL), and root system volume (RSV), as well as decreased total phosphorus (TP) and total dry matter (TDM). The largest reductions were observed with TDM, TP, MBL, NL, and RSV, with losses of 77.3, 70.5, 64.8, 60.0, and 47.7%, respectively (Table 1). ANOVA revealed a significant effect of the interaction between genotypes and phosphorus levels ($p < 0.01$) for all characteristics evaluated, except for the relative chlorophyll index (RCI).

The reduction in the aforementioned variables in plants cultivated under phosphorus restriction (P-), is in agreement with the results of previous studies (Fita et al., 2012; Li et al., 2018). This reduction in morphological characteristics related to plant development and growth is likely due to the fact that phosphorus is a constituent element in molecules such as nucleic acids, adenosine triphosphate, and phospholipids, and acts as an essential metabolic regulator for processes such as energy transfer, protein activation, and carbon and nitrogen metabolism (Shen et al., 2011).

Under phosphorus restriction (P-), there was an increase in RSL, $\text{P}_{(\text{R/S})}$, and $\text{DM}_{(\text{R/S})}$ (Table 1). According to Taiz et al. (2017), under P restriction, the plant root system undergoes changes, such as a reduction in primary root elongation, an increase in proliferation and elongation of lateral roots, and an increase in the amount of hair. These can be explained by the reallocation of resources to the root system to promote greater development and expansion of the exploitation capacity of roots.

Fita et al. (2012) evaluated the root system of melons under two phosphorus levels and observed a reduction in the dominance of the main root, especially in accessions of the Agrestis group under phosphorus restriction. Research with other species, such as watermelons (Meng et al., 2014), beans (Shanka et al., 2018) and sweet potatoes (Li et al., 2020) corroborate the results of the current study.

Phosphorus concentration had no significant effect on the chlorophyll index (RCI) (Table 1). This result differs from that of Li et al. (2018), who studied the effect of P on chloroplasts in melon in a hydroponic system and concluded that a phosphorus restriction inhibited the activity of the photosystem and caused photooxidative stress and photoinhibition. In watermelons grown in a greenhouse under a floating system, photosynthesis in all genotypes significantly decreased under stress conditions (Meng et al., 2014).

According to Fahad et al. (2021), phosphorus restriction causes abnormalities in chloroplast morphology, as well as a

Table 1. General averages of the evaluated characteristics in 10 melon genotypes cultivated in hydroponic solutions with and without phosphorus restriction

Solution	Characteristic				
	NL	SD (cm)	MBL (cm)	RSL (cm)	RSV (cm^3)
P+	26.90	7.62	71.15	48.33	40.25
P-	10.75	6.40	25.05	72.50	21.05
F (G × P)	115.37**	20.20**	104.46**	33.36**	39.02**
	RCI	$\text{P}_{(\text{R/S})}$ (mg per plant)	TP (mg per plant)	$\text{DM}_{(\text{R/S})}$ (g)	TDM (g)
P+	37.64	0.62	40.85	0.16	13.52
P-	36.92	0.90	12.05	0.32	3.07
F (G × P)	0.77$^{\text{ns}}$	40.45**	729.81**	150.53**	330.57**

F (G × P) - F value of the interaction between genotypes (G) and phosphorus concentrations (P); $^{\text{ns}}$, ** - Not significant and significant by F test ($p \leq 0.01$) respectively; NL - Number of leaves; SD - Stem diameter; MBL - Main branch length; RSL - Root system length; RSV - Root system volume; RCI - Relative chlorophyll index; $\text{P}_{(\text{R/S})}$ - Root and shoot phosphorus concentration ratio; TP - Total phosphorus; $\text{DM}_{(\text{R/S})}$ - Root and shoot dry matter ratio; TDM - Total dry matter; P+ - Solution without phosphorus restriction; P- - Solution with phosphorus restriction reduction in cell expansion, photosynthesis, and respiration. The lack of a significant effect on the relative chlorophyll index in the current study shows that further studies and an estimation of other characteristics involved in photosynthesis are needed to detect differences in melon germplasm with regard to this parameter.

The average estimates for the characteristics related to plant morphology, root system, dry mass, phosphorus, and chlorophyll concentrations in the two nutrient solutions are shown in Table 2. The genotypes 'GCC,' A-29, and A-52, in which were allocated to the first group, showed greater NLs in the solution without phosphorus restriction, while 'Vereda,' A-02, A16, A-29, A-50, and A-52 dominated in the phosphorus-restricted solution. Regarding SD, 'GRC,' Aca,' 'GCC,' 'Trinity,' A-29, and A-52 had the greatest values in P+, while in the P-solution, only A-16 and A-50, showed lower performances for that characteristic.

Regarding the features related to the root system, the 'GCG' genotype predominated in terms of the length of the main branch in the P+ solution, while 'GCC' and A-52 prevailed in the P- solution (Table 2). Regarding RSL, there was no significant difference among the genotypes treated with the P+ solution; however, in the solution with P restriction, A-16, A-29, A-50, and A-52 showed the greatest RSLs. Considering RSV in the P+ solution, the formation of two groups was observed, with prominence for 'Aca,' 'GCC,' 'Trinity', A-02, A-16, and A-50. In the P-solution, the genotypes with the best performance were 'GCC,' A-50, and A-52.

The genotypes did not differ in terms of the chlorophyll index in either solution; therefore, they were grouped together (Table 2). For the $P_{(R/S)}$, the solution with high phosphorus concentration (P+), formed three groups of genotypes, with emphasis on 'Trinity,' A-16, and A-29. In the P- solution, there was little discrimination between the genotypes, with the formation of two groups, one of which included only the 'Vereda' genotype, with a lower $P_{(R/S)}$ ratio. Considering TP characteristics, two groups of genotypes were formed in the two solutions. In the P+ solution, the most prominent genotypes were 'Vereda,' 'GRC,' 'Aca,' A-02, and A-16. In the P- solution, the hybrid 'Vereda,' had the highest phosphorus concentration.

In the P+ solution, the two highest average estimates for the variable $DM_{(R/S)}$ were observed in 'GRC' and A-50 (Table 2). There was greater discrimination among the genotypes in the P- solution with the formation of three groups. The genotype 'Aca,' which was the only member of the first group, had the highest estimate for that feature. The formation of three groups for total dry matter in the P+ solution was observed, with an emphasis on the genotype 'GCC'. In the P- solution, two groups were formed, with an emphasis on genotypes A-29, A-52, A-50, and A-16.

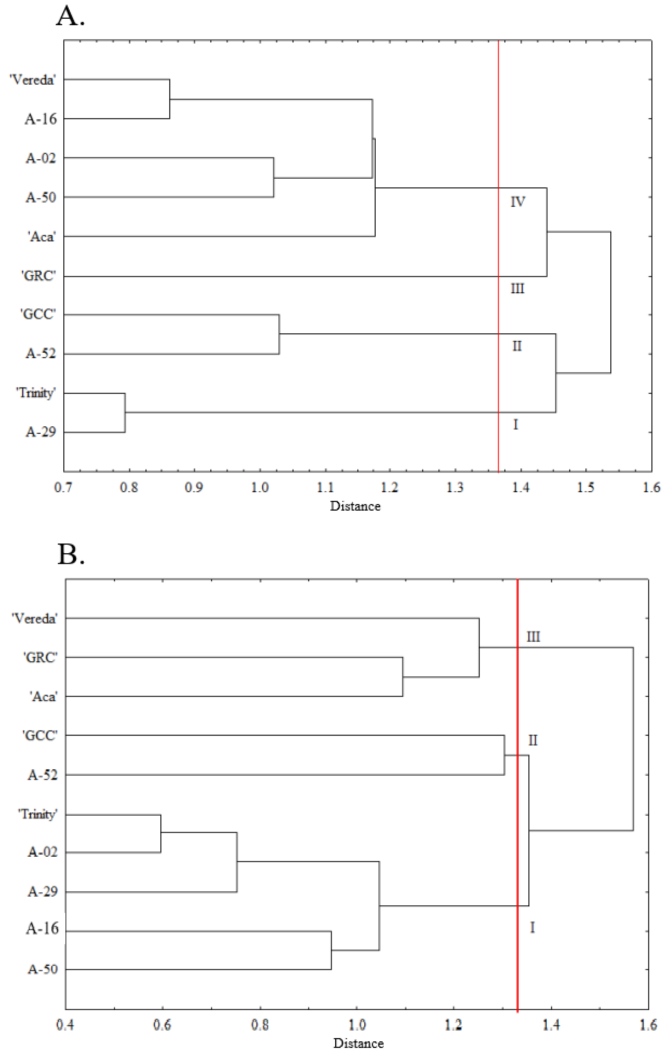
When considering the simultaneous analysis of the characteristics, significant differences were found among the genotypes (F_{Wilks} = 6.23), which were allocated to distinct groups depending on the solution used, confirming the presence of genetic variability (Figures 1A and B). The two groupings can be considered reliable because the cophenetic correlation estimates for both were greater than 0.70, indicating small differences between the original distance matrix and the grouping matrix.

For the P+ solution, four groups were formed (Figure 1), with the first containing 'Trinity' and A-29; the second, 'GCC' and A-52; and the third, only 'GRC.' The fourth consisted of

Table 2. Average of the evaluated characteristics of 10 melon genotypes cultivated in hydroponic solutions with and without phosphorus restriction

Genotype	NL	SD	MBL	RSL	RSV	RCI	$P_{(R/S)}$	TP	$DM_{(R/S)}$	TDM
		(cm)			(cm³)		(mg per plant)		(g)	
Solution P+										
'Vereda'	22.50 b	7.20 b	70.25 c	46.75 a	31.25 b	37.38	0.61 b	48.43 a	0.13 b	8.38 c
'GRC'	27.50 b	7.58 a	57.50 d	50.50 a	22.50 b	40.40	0.44 c	42.67 a	0.26 a	14.74 b
'Aca'	20.50 b	8.25 a	53.50 d	47.25 a	51.25 a	33.79	0.64 b	46.31 a	0.14 b	11.54 c
'GCC'	39.50 a	8.53 a	112.5 a	44.25 a	51.25 a	38.95	0.33 c	37.31 b	0.15 b	19.04 a
'Trinity'	26.50 b	8.18 a	73.25 c	58.50 a	42.50 a	36.73	0.83 a	37.81 b	0.16 b	14.10 b
A-02	24.00 b	7.15 b	72.25 c	41.75 a	57.50 a	37.84	0.44 b	41.55 a	0.14 b	14.32 b
A-16	22.50 b	6.65 b	46.25 d	48.75 a	40.00 a	40.48	0.79 a	45.05 a	0.17 b	10.38 c
A-29	31.00 a	7.83 a	85.00 b	59.25 a	26.25 b	38.94	0.93 a	34.02 b	0.12 b	15.30 b
A-50	20.50 b	6.33 b	52.75 d	46.50 a	45.00 a	35.70	0.62 b	35.19 b	0.20 a	12.67 c
A-52	34.50 a	8.53 a	88.50 b	39.75 a	35.00 b	36.20	0.60 b	40.20 b	0.13 b	14.79 b
CV (%)	38.52	17.15	41.54	33.82	48.06	9.42	27.24	15.47	29.80	30.34
Solution P-										
'Vereda'	10.00 a	6.43 a	26.75 b	61.25 b	15.00 b	38.06	0.40 b	19.69 a	0.33 b	2.50 b
'GRC'	8.25 b	6.38 a	23.00 b	61.75 b	12.50 b	41.79	1.03 a	11.61 b	0.34 b	2.09 b
'Aca'	5.00 b	6.83 a	20.75 b	49.00 b	17.50 b	35.71	0.90 a	12.34 b	0.61 a	2.06 b
'GCC'	8.75 b	6.60 a	41.75 a	69.00 b	25.00 a	33.84	0.77 a	10.90 b	0.35 b	2.54 b
'Trinity'	9.25 b	6.78 a	19.75 b	67.00 b	21.75 b	36.19	1.20 a	10.83 b	0.26 c	3.05 b
A-02	12.50 a	6.55 a	16.25 b	72.25 b	22.50 b	36.06	0.84 a	11.07 b	0.26 c	3.25 b
A-16	10.50 a	5.55 b	15.75 b	92.75 a	22.50 b	39.20	1.01 a	14.03 b	0.17 c	3.54 a
A-29	14.25 a	6.65 a	26.75 b	80.00 a	21.25 b	35.69	1.04 a	11.26 b	0.24 c	4.07 a
A-50	13.25 a	5.25 b	17.50 b	89.25 a	25.00 a	32.58	0.98 a	10.51 b	0.34 b	3.59 a
A-52	15.75 a	7.05 a	42.25 a	82.75 a	27.50 a	40.08	0.80 a	8.24 b	0.25 c	3.99 a
CV (%)	19.12	14.63	27.45	28.77	30.68	9.87	27.02	14.50	20.24	22.70

Averages followed by the same letter belong to the same group by the Scott-Knott's test ($p \leq 0.05$). CV (%) - coefficient of variation; GRC - Gaúcho Redondo Conesul; Aca - Amarillo Canário; GCC - Gaúcho Casca de Carvalho; NL - Number of leaves; SD - Stem diameter; MBL - Main branch length; RSL - Root system length; RSV - Root system volume; RCI - Relative chlorophyll index; $P_{(R/S)}$ - Root and shoot phosphorus concentration ratio; TP - Total phosphorus; $DM_{(R/S)}$ - Root and shoot dry matter ratio; TDM - Total dry matter; P+ - Solution without phosphorus restriction; P- - Phosphorus-restricted solution



The red line corresponds to the cut-off for splitting groups at 80% of the maximum distance. r - cophenetic correlation coefficient

Figure 1. Dendrogram generated by UPGMA from the Mahalanobis distances among melon genotypes cultivated in hydroponic solutions without (A) and with (B) phosphorus restriction

50% of the genotypes ('Aca,' A-50, A-02, A-16, and 'Vereda'). Three groups of genotypes were formed in the solution with phosphorus restriction (P-). The first group consisted of 'Trinity,' A-02, A-29, A-16, and A-50. The second group consisted of genotypes 'GCC' and A-52, and the third group contained the three improved genotypes 'Aca,' 'GRC,' and 'Vereda.'

The evaluated genotypes showed differences in breeding stage. The multivariate analysis did not group the genotypes according to their degree of improvement in the solution without phosphorus restriction (P+), and included both improved and non-improved materials in the formed groups. However, in the P-solution, there was a tendency to group materials according to their level of improvement, with a few exceptions (Figure 1).

This indicates the presence of an interaction between genotypes and phosphorus concentrations (Table 1); that is, there is a different behavior of the genotypes as a result of phosphorus availability. Studies have shown genotypic heterogeneity in several other species under different conditions of phosphorus availability (Uzokwe et al., 2017; Bernardino et al., 2019; Li et al., 2020). Genetic variability is essential for breeders to conduct breeding programs aimed at obtaining cultivars that are efficient in phosphorus use.

The variables that contributed the most to genetic divergence in the P+ solution were MBL and RSV, while RSL and MBL dominated in the P- solution (Table 3). SD had the smallest contribution in both situations.

The evaluated genotypes showed greater phosphorus use efficiency (PUE) and phosphorus internal use efficiency (PIUE) when this nutrient was restricted (P-), whereas the highest phosphorus acquisition efficiency (PAE) was observed with the P+ solution (Table 4).

Regarding PUE, the genotypes 'GCC' and A-29 were the most efficient in the P+ solution. In the situation of phosphorus restriction (P-), 'Trinity,' A-02, A-16, A-29, A-50, and A-52 were the most efficient (Table 4). Concerning the PAE, in the P+ solution, the genotypes 'Vereda,' 'Aca,' 'GCC,' 'Trinity,' A-29, and A-52 prevailed. In the P-solution, only 'Vereda' was efficient. The genotypes with the highest PIUE, in the P+ solution, were the 'GCC' and A-29 genotypes, while, in the P- solution, the most efficient genotypes were 'Trinity,' A-02, A-29, and A-52 (Table 4).

Fita et al. (2012) also observed differences in acquisition and use efficiencies among melon accessions from different botanical groups, with accessions from the Agrestis group dominating. Those authors observed greater expression of genes related to P mobilization and remobilization in three other efficient accessions (flex-Ac, in-Am, and mo-kha) and lower expression in less efficient accessions for phosphorus use (chi-SC, ma-YP, and ca-NC), suggesting that P mobilization and remobilization should be a preferential source of diversity when adapting melon genotypes to P restriction.

The genotypes 'GCC,' A-29, and A-52 had the greatest PAE and PIUE in the solution with the highest availability of phosphorus (Figure 2A). The 'Trinity,' 'Aca,' and 'Vereda' genotypes showed PAEs above the average, but PIUEs below the average value. The PAE and PIUE values of the other genotypes were lower than their respective averages (Figure 2). Genotypes A-29 and A-52 dominated in the phosphorus-restricted environment with PAE and PIUE values above the average (Figure 2B). The genotypes A-16 and 'Vereda' had an above average PAE, but a PIUE below the average value.

Table 3. Contribution of variables to genetic divergence among melon genotypes cultivated in hydroponic solutions without (P+) and with (P-) phosphorus restriction

Character	S_j (%)	
	Solution P+	Solution P-
Number of leaves (NL)	6.08	2.76
Stem diameter (SD)	0.09	0.09
Main branch length (MBL)	58.01	25.35
Root system length (RSL)	6.17	58.81
Root system volume (RSV)	19.90	5.94
Relative chlorophyll index (RCI)	0.68	2.16
Root and shoot phosphorus concentration ratio [$P_{(R/S)}$]	1.76	0.10
Total phosphorus (TP)	0.52	1.77
Root and shoot dry matter ratio [$DM_{(R/S)}$]	1.40	0.23
Total dry matter (TDM)	3.51	2.49

S_j (%) - Relative contribution of variables (Singh, 1981)

Table 4. Average phosphorus use efficiency (PUE), phosphorus acquisition efficiency (PAE), and phosphorus internal use efficiency (PIUE) indexes in melon genotypes cultivated in hydroponic solutions without (P+) and with (P-) phosphorus restriction

Genotype	PUE		PAE		PIUE	
	P+	P-	P+	P-	P+	P-
‘Vereda’	36.69 b	34.76 b	0.52 a	0.29 a	61.27 c	283.65 b
‘GRC’	34.91 b	28.99 b	0.43 b	0.13 b	66.79 c	234.18 b
‘Aca’	30.71 b	27.68 b	0.47 a	0.14 b	62.03 c	208.62 b
‘GCC’	47.40 a	39.52 b	0.51 a	0.12 b	121.07 a	271.84 b
‘Trinity’	37.72 b	44.76 a	0.46 a	0.14 b	78.16 b	316.16 a
A-02	38.64 b	50.49 a	0.34 b	0.14 b	77.44 b	323.16 a
A-16	30.03 b	49.20 a	0.40 b	0.18 b	73.16 b	282.75 b
A-29	48.84 a	62.50 a	0.53 a	0.20 b	106.67 a	312.19 a
A-50	32.29 b	49.83 a	0.44 b	0.15 b	85.28 b	265.53 b
A-52	41.95 b	55.42 a	0.47 a	0.17 b	88.80 b	378.32 a
P+	37.47		0.46		81.33	
P-	43.08		0.17		277.56	
F (G × P)	0.27^{ns}		0.00^{ns}		7.18**	

Averages followed by the same letter belong to the same group by the Scott-Knott’s test ($p \leq 0.05$). F (G × P) - F value of the interaction between genotypes (G) and phosphorus concentrations (P); ^{ns}, ** - Not significant and significant by F test ($p \leq 0.01$) respectively. GRC - Gaúcho Redondo Conesul; Aca - Amarillo Canário; GCC - Gaúcho Casca de Carvalho

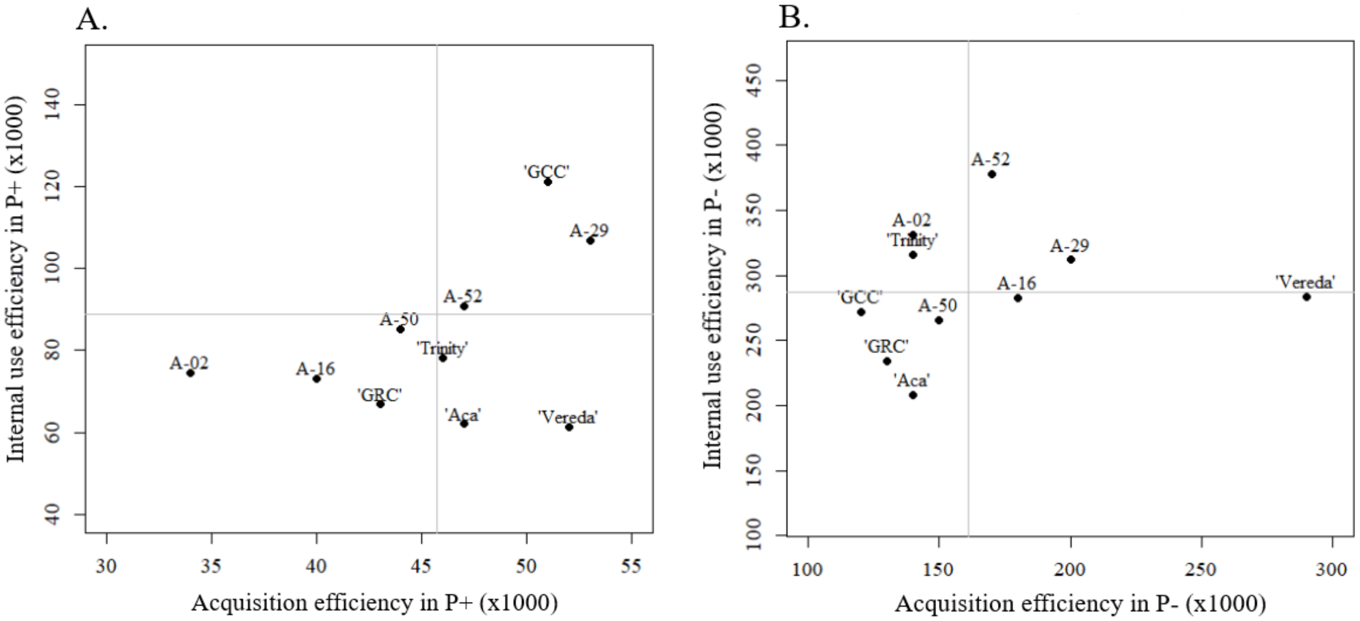


Figure 2. Dispersion of genotypes evaluated as a result of acquisition efficiencies and internal use in hydroponic solutions without (A) and with (B) phosphorus restriction

In the solution with a high phosphorus P+ concentration, PIUE contributed close to 70% of the sum of squares of PUE, with a correlation between the two variables of $r_{(XiY)} = 0.90^{**}$ (Table 5). In contrast, with P restriction, the result was opposite, whereby PAE explained most of the PUE (66.08%) with a correlation of $r_{(XiY)} = 0.87^{**}$ (Table 5).

Similar results were found by Bernardino et al. (2019) who concluded that PAE was the most important component for PUE under phosphorus restriction in a sorghum crop.

Understanding the contributions of the PAE and PIUE components to the PUE is important because each of these factors depends on different mechanisms. The mechanisms

Table 5. Contribution of the sum of squares of genotypes (SQ_{Gen}) of phosphorus acquisition efficiency and phosphorus utilization efficiency to the sum of squares of phosphorus use efficiency and correlation coefficient between Xi and Y (r_{XiY}), and S_{Xi}/S_Y ratio in hydroponic solutions without (P+) and with (P-) phosphorus restriction

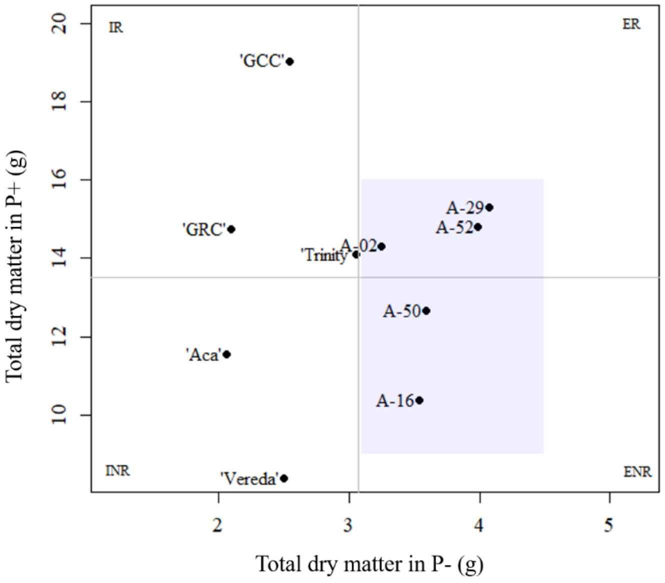
Character	(SQ_{Gen})	Contribution of X_i for (SQ_Y)	$r_{(XiY)}$	(S_{Xi}/S_Y)
		Solution (P+)		
Acquisition efficiency (X_1)	0.0456	31.15	0.68	0.45
Utilization efficiency (X_2)	0.1013	68.85	0.90	0.76
Use efficiency (Y)	0.1469			
		Solution (P-)		
Acquisition efficiency (X_1)	0.1262	66.08	0.87	0.68
Utilization efficiency (X_2)	0.0648	33.92	0.67	0.90
Use efficiency (Y)	0.1910			

related to the acquisition of phosphorus, especially in situations of restriction of this nutrient, are root changes, microorganism associations, rhizosphere changes, and biochemical changes. The mechanisms related to internal phosphorus utilization are the transfer and distribution of P in the plant, internal remobilization, and distribution of P in the vacuoles (Shen et al., 2011; Irfan et al., 2020). Accordingly, quantification of the correlation between PAE and PIUE with PUE helps researchers focus on understanding the most important mechanisms involved in the evaluated genotypic variation.

The independence of PAE and PIUE has been observed by other authors (Hu et al., 2010), suggesting that there are two complementary ways to increase the usage efficiency under phosphorus restriction. In other words, simultaneous selection of both efficiencies is possible. In the current study, the estimates in the P+ and P- solutions were nonsignificantly positive and of reduced magnitudes. When considering the two efficiencies, it was possible to identify two accessions with PAE and PIUE values above the average of the evaluated group (A-29 and A-52).

In addition to using nutrients efficiently, it is important that genotypes are responsive. A practical way to identify responsive genotypes is to plot their respective dry matter values under conditions of greater and lesser availability of phosphorus (Li et al., 2018). This allows the classification of genotypes into four classes regarding efficiency and responsiveness: efficient and responsive (ER), efficient and non-responsive (ENR), inefficient and responsive (IR), and inefficient and non-responsive (INR) (Figure 3).

Genotypes A-02, A-29, and A-52 were classified as ER, that is, they contained above average dry matter in both solutions (with and without phosphorus restriction). Genotypes A-16 and A-50 were placed in the second quadrant and classified as ENR, dry matter above the average in solution with phosphorus restriction, but below the average when there was no phosphorus restriction (P+). The genotypes 'Vereda' and 'Aca' were classified as INR, with lower dry matter values in both conditions. Finally, the genotypes 'GCC,' 'GRC,' and 'Trinity' were classified as IR, with higher than the average dry matter in the solution without phosphorus restriction (P+) and lower than the average in the solution with phosphorus restriction (P-).



ER - Efficient and Responsive; ENR - Efficient and Non-Responsive; INR - Inefficient and Non-responsive; IR - Inefficient and Responsive

Figure 3. Dispersion of genotypes evaluated as a function of dry matter (g) in hydroponic solutions without (P+) and with (P-) phosphorus restriction

To aid researchers in the selection of more efficient and responsive genotypes, a selection index (SI) was created considering the dry matter of the genotypes evaluated at the two phosphorus levels. The most prominent genotypes (highest index) were A-52, A-29, A-50, A-16, and 'Trinity,' and of the five genotypes, four were not improved (Figure 4).

Maia et al. (2011) emphasized that it is important not only to consider the efficiency of use but also the tolerance of genotypes under phosphorus stress conditions. The selection index (SI) was used to measure phenotypic plasticity, which is the ability of each genotype to present functional adaptive responses in relation to environmental variations (Schneider & Lynch, 2020). Therefore, genotypic variability was found, with emphasis on A-29, A-50, and A-52, because they showed greater plasticity.

Two groups of genotypes were evaluated in the current study. The first group was represented by five improved genotypes of different types of melon ('Vereda,' 'GRC,' 'Aca,' 'GCC,' and 'Trinity') and the second by five accessions collected from roads or small properties, four of which were of the botanical variety momordica (A-02, A-29, A-50, and A-52) and the other was from the acidulus group (A-16).

Modern cultivars have been obtained under selective conditions with high availability of phosphorus and other nutrients through the application of fertilizers. Under these conditions, some alleles related to efficient nutrient acquisition are lost, since the nutrients are directly available to plants. For this reason, the adaptive characteristics of plants in response to nutrient shortages often result in additional carbon costs, thus impairing biomass or grain production (Li et al., 2018).

Considering the individual PAE values in the two solutions (P+ and P-), there was little variation in the P + solution between the two groups and reduced variation in the P- solution in the non-improved group. The hybrid 'Vereda' had the highest PAE in P-, and was the only one that differed from the other evaluated genotypes (Figure 2).

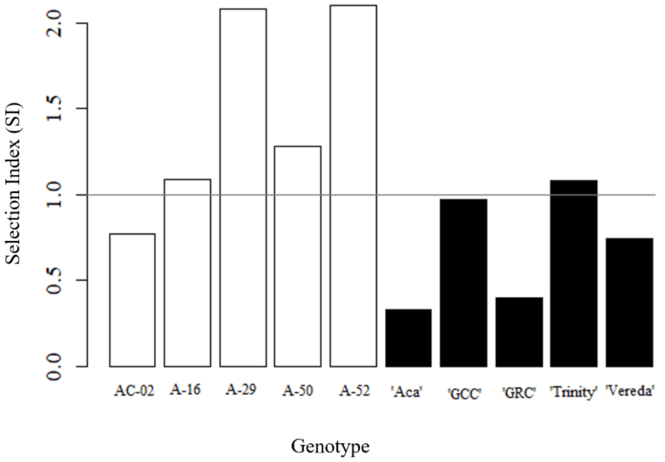


Figure 4. Selection index (SI) of melon genotypes cultivated in hydroponics without (P+) and with (P-) phosphorus restriction

Wang et al. (2010) stated that the great challenge to increase the efficiency of P use in modern cultivars is to change the mechanisms related to PIUE to obtain higher yields. The average of the non-improved genotypes was higher than that of the improved group in both solutions, although this contrast was much smaller in the P+ solution because the genotype with the highest PIUE, 'GCC,' belonged to the improved group, and increased the average of that group. This shows that there is variability among and within groups for PIUE. Under phosphorus restriction (P-), there was less variation within each group.

Considering the efficiencies simultaneously in the P+ solution, the genotypes A-29 and A-50 (non-improved) and 'GCC' (improved) showed above-average behavior for PAE and PIUE. Of the four genotypes with the poorest PAE and PIUE performances, four were not improved. In the P- solution, genotypes A-29 and A-50 were superior, whereas among the four materials with the poorest performance, three were improved. Based on these results, it is possible to obtain genotypes with high PAE and PIUE (Hu et al., 2010).

All non-improved genotypes were among the most efficient genotypes, and A-02, A-29, and A-50 were also responsive. From the improved group, all were considered inefficient, with three being responsive ('GCC,' 'GRC,' and 'Trinity').

Among the five most tolerant genotypes, four were from the non-improved group (A-16, A-29, A-50, and A-52). Improved genotypes tend to show, on average, less plasticity because they had been selected for conditions with advanced technology cultivation and greater fertilizer application (Wang et al., 2010). In general, the unimproved genotypes were more responsive but less productive than the cultivars, but could be used as alternatives for marginal areas with phosphorus restriction.

CONCLUSIONS

1. Under phosphorus restriction, the use and internal utilization efficiencies were increased and the acquisition efficiency was reduced.

2. In the restriction of phosphorus, the non-improved genotypes presented greater efficiency of use and internal use of phosphorus than the cultivars and similar acquisition efficiencies.

3. Under phosphorus restriction, genotypes A-16, A-29, A-50, A-52, and 'Trinity' were classified as efficient and responsive, showing promise for use in genetic improvement programs.

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