CULTIVAR RELEASE

UENF P01, UENF P02 and UENF P03: popcorn hybrids with high phosphorus use efficiency

Crop Breeding and Applied Biotechnology
23(1): e44102318, 2023
Brazilian Society of Plant Breeding.
Printed in Brazil
http://dx.doi.org/10.1590/1984-70332023v23n1c8

Antonio Teixeira do Amaral Jr.[1], Ismael Fernando Gerhardt[1], Rodrigo Moreira Ribeiro[1*], Valter Jario de Lima[1], Samuel Henrique Kamphorst[1], Flávia Nicácio Viana[1], Katia Fabiane Medeiros Schmitt[1], Jhean Torres Leite[1], Divino Rosa dos Santos Junior[1], Talles de Oliveira Santos[1], Rosimeire Barboza Bispo[1], Carolina Macedo Carvalho[1] and Pedro Henrique Araújo Diniz Santos[1]

Abstract: *The hybrids are responsive to phosphorus application, have high use efficiency and can produce high mean yields in environments with low and high phosphorus. The mean PE of these hybrids is high, therefore they are recommended for cultivation in the North and Northwest regions of Rio de Janeiro State, Brazil.*

Keywords: *Plant breeding, abiotic stress, nutritional efficiency, sustainable agriculture*

INTRODUCTION

In view of the current climate changes, a more sustainable agriculture is urgently needed, adapted to the different abiotic stresses of crops (Gerhardt et al. 2019). To meet this challenge, one of the possible answers is to breed more efficient cultivars adapted to environments with low phosphorus (P) availability, as in the case of Brazilian soils, to be able to decrease agricultural inputs and reduce environmental pollution and production costs (Conceição-Silva et al. 2019).

Phosphorus is one of the most relevant primary macronutrients for nearly all crop species, due to the functions of this nutrient in vital plant mechanisms (Zeng et al. 2022). To meet the growing demand for P fertilizers, phosphate rock mining increased fivefold between the 1960s and 2011 (Scholz et al. 2013), and the global production of P fertilizers increased at an annual rate of 4% (Barros et al. 2022). The reserves of this non-renewable natural resource are likely to be exhausted within the next 50 years (March et al. 2016). Plant performance must therefore be optimized to increase P use efficiency and responsiveness to P application (Gerhardt et al. 2019). This will be relevant for the sustainability of production systems, especially on soils in tropical regions, where fertility is low and acidity and P adsorption capacity are high (Barros et al. 2022).

Particularly for popcorn production, which generates an annual turnover of about 1 billion dollars in the USA, to date all improved seed planted in Brazil must be imported, due to its higher grain yield and popping expansion, which

***Corresponding author:**
E-mail: rodrigo.moreira85@yahoo.com.br
ORCID: 0000-0001-7152-3114

Received: 29 November 2022
Accepted: 04 March 2023
Published: 20 March 2023

[1] Universidade Estadual do Norte Fluminense Darcy Ribeiro, Avenida Alberto Lamego, 2000, Parque California, 28013-602, Campos dos Goytacazes, RJ, Brazil

has motivated the development of research at the State University of Northern Rio de Janeiro (UENF), whose focus is the development of productive cultivars, with high expansion capacity, resistant to the main pathogens and pests and with better use of P. Genotypes are being developed with tolerance or resistance to biotic stresses (Schwantes et al. 2018, Amaral Júnior et al. 2019, Schmitt et al. 2019, Santos et al. 2020, Almeida et al. 2021, Kurosawa et al. 2021); to abiotic stresses, in particular drought (Lima et al. 2021, Santos et al. 2021, Kamphorst et al. 2022, Leite et al. 2022, Viana et al. 2022), to low nitrogen (Santos et al. 2020, Khan et al. 2021, Khan et al. 2022) and to low P availability (Gerhardt et al. 2017, Gerhardt et al. 2019, Santos et al. 2021). In addition, genome wide selection (GWS) in a recurrent intrapopulation selection program was used to accelerate the breeding of superior segregating generations (Mafra et al. 2019, 2020, Albino-Schwantes et al. 2020, Schwantes et al. 2020). The objective of this present study was to meet the demand for cultivars adapted to Brazilian conditions, as cultivation options in the regional and national agribusiness. As a result, three single-cross popcorn hybrids, designated UENF P01, UENF P02 and UENF P03, with improved P use efficiency, are presented here for the North and Northwest regions of Rio de Janeiro State.

BREEDING METHOD

The hybrids UENF P01, UENF P02 and UENF P03 resulted from a cross between the lines P7 x L80, P7 x L76 and P6 x L80, respectively. Lines P7 and P6 were derived from the hybrid Zaeli and lines L80 and L76 from population 'Viçosa' (Figure 1). These genotypes are maintained at the Active Germplasm Bank of the State University of Northern Rio de Janeiro – UENF (Table 1). Before the registration of these hybrids by the Ministry of Agriculture, Livestock and Food Supply (MAPA), the parents and hybrids were systematically evaluated, according to the norms and minimum requirements for the determination of the Value for Cultivation and Use (VCU) for specialty maize types, with a view to the inclusion in the National Registry of Cultivars (MAPA 2020).

Initially, 25 popcorn S_7 lines of the UENF Popcorn Breeding Program were evaluated for P use efficiency and responsiveness to P application (Table 1). To this end, experiments were conducted at two locations and in two environments with different P availability, namely: Antonio Sarlo State College of Agriculture, in the district of Campos dos Goytacazes, Rio de Janeiro (RJ) and at the Experimental Station of Itaocara - RJ, Brazil. In a pre-experimental stage, the soils were chemically analyzed to determine P availability, based on 10 soil subsamples (0-10- and 10-20-cm layers), blended in a composite sample. The P availability (classified as low) and clay contents in the soils from Campos dos Goytacazes and Itaocara were, respectively, 8 and 11 mg dm^3 of P and 305 and 140 g dm^3 of clay. The climate that characterizes the municipalities of Campos dos Goytacazes

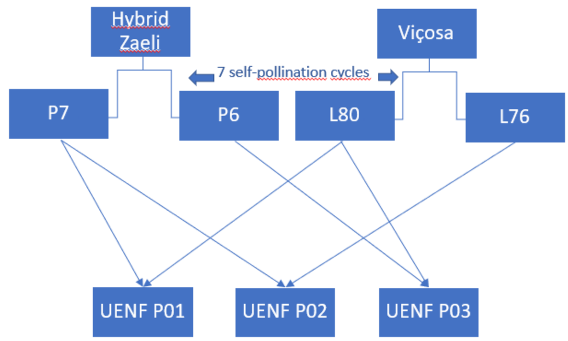

Figure 1. Scheme of the development of hybrids UENF P01, UENF P02 and UENF P03.

Table 1. Popcorn S_7 lines with the respective genealogies and climatic adaptations

Line	Population of origin	Climate adaptation
L53	Beija-flor: UFV	Temperate/ Tropical
L54	Beija-flor: UFV	Temperate/ Tropical
L59	Beija-flor: UFV	Temperate/ Tropical
L61	BRS Angela: EMBRAPA	Tropical
L63	BRS Angela: EMBRAPA	Tropical
L65	BRS Angela: EMBRAPA	Tropical
L66	BRS Angela: EMBRAPA	Tropical
L69	BRS Angela: EMBRAPA	Tropical
L70	BRS Angela: EMBRAPA	Tropical
L71	BRS Angela: EMBRAPA	Tropical
L75	Viçosa: UFV	Temperate/ Tropical
L76	Viçosa: UFV	Temperate/ Tropical
L77	Viçosa: UFV	Temperate/ Tropical
L80	Viçosa: UFV	Temperate/ Tropical
L88	Viçosa: UFV	Temperate/ Tropical
P1	Hybrid Zélia	Temperate/ Tropical
P2	Composite CMS-42: EMBRAPA	Temperate/ Tropical
P3	Composite CMS-42: EMBRAPA	Temperate/ Tropical
P4	South American races	Temperate/ Tropical
P5	Hybrid Zaeli	Temperate/ Tropical
P6	Hybrid Zaeli	Temperate/ Tropical
P7	Hybrid Zaeli	Temperate/ Tropical
P8	Hybrid IAC-112	Temperate/ Tropical
P9	Hybrid IAC-112	Temperate/ Tropical
P10	Hybrid IAC-112	Temperate/ Tropical

and Itaocara is classified as Tropical climate (Aw), with hot summers and mild winters, with a tendency for rainfall to be concentrated in the summer months and the soil has a sandy-clay texture.

A randomized block design with four replications was used. Each experimental plot consisted of one 5-m row, with plants spaced 0.20 m apart within rows and a row spacing of 0.90 m, i.e., 25 plants per plot.

To prepare the environment with optimum P availability, fertilization at planting was applied as follows: 30 N kg ha^{-1}, 70 P_2O_5 kg ha^{-1} and 40 K_2O kg ha^{-1}. For the low-P environment, fertilization consisted of 30 N kg ha^{-1}, 0 P_2O_5 kg ha^{-1}, and 40 K_2O kg ha^{-1}. In both environments, the soil was top-dressed with 100 N kg ha^{-1} at the phenological stage V6.

The supply capacity of primary macronutrients in the experimental areas was optimized by fertilization, according to the recommendations for popcorn and as indicated by soil chemical analysis (0-20-cm layer) for some nutrients, with exception of the intentionally low P level in the environment with low P availability, with zero fertilization.

As a result, eight lines were selected for hybrid breeding (Table 2). Of these eight, three lines were classified as highly P-use efficient and responsive to P application (ER), three others were classified as the most inefficient and non-responsive to P application (INR) and two were classified as moderately P-use efficient and responsive (Gerhardt et al. 2017). The ER lines were P2, P7 and L59; the INR lines L77, L75 and L80; and the intermediate lines P6 and L76. It is worth mentioning that contrasting genotypes were used, based on the premise of maximum heterotic expression.

Twenty-eight hybrids were generated by a complete diallel between lines, without reciprocals. The hybrids and parents were evaluated at the same two locations, under the same environmental conditions where the lines had been selected, in a 6 x 6 triple lattice design. Sowing was carried out in a conventional planting system. Each experimental plot consisted of one 5.00 m row, with plants spaced 0.20 m apart within rows at a row spacing of 0.70 m, i.e., 25 plants per plot.

For the ER tests, selection was performed based on the mean grain yield between the environments and lowest P demand of the cultivars. In addition, the morphological traits and other agronomic traits were evaluated, namely: popping expansion, male and female flowering, mean plant and ear height, as well as yield components (mean ear diameter, mean ear length and mean 100-grain weight). The coefficients of experimental variation of the traits were estimated, as well as the means of cultivars and controls, the experimental means for each location and year, and the combined means.

Table 2. Estimates of mean grain yield (YLD), popping expansion (PE) and popping expansion volume per hectare (VP) of 36 popcorn genotypes grown in environments with low and high phosphorus availability

Genotype	**YLD** (kg ha^{-1})		**PE** (mL g^{-1})	
	Low P	**High P**	**Low P**	**High P**
P2	1437.35 e	1796.83 f	20.96 d	21.80 d
P7	1707.80 d	2127.77 e	27.22 b	30.80 a
L59	1905.77 d	2472.76 d	23.04 c	24.00 c
P6	1552.54 e	1729.02 f	24.01 c	26.70 c
L76	953.71 f	1124.97 g	26.29 b	27.90 b
L77	507.03 g	774.90 h	26.05 b	25.30 c
L75	386.35 g	504.50 i	20.00 d	20.10 d
L80	343.90 g	401.19 i	29.49 a	31.00 a
P2 x P7	2359.40 c	2006.47 e	25.22 b	27.48 b
P2 x L59	1951.18 d	1773.51 f	22.83 c	23.06 d
P2 x P6	1990.21 d	2184.32 e	22.72 c	25.00 c
P2 x L76	1814.20 d	2083.60 e	24.70 c	24.85 c
P2 x L77	2007.60 d	2159.76 e	23.63 c	25.73 c
P2 x L75	2491.73 c	2857.63 c	23.53 c	21.52 d
P2 x L80	1905.39 d	2134.87 e	24.49 c	26.58 c
P7 x L59	2905.84 b	3333.46 b	29.69 a	27.92 b
P7 x P6	2293.87 c	2613.54 d	28.33 a	30.56 a
P7 x L76	2960.35 b	3213.04 b	29.59 a	29.71 a
P7 x L77	2736.51 b	3106.86 b	27.36 b	30.58 a
P7 x L75	3058.55 b	3284.67 b	27.33 b	26.37 c
P7 x L80	3057.82 b	3134.64 b	29.32 a	31.44 a
L59 x P6	2690.12 b	2899.81 c	25.92 b	26.15 c
L59 x L76	1737.63 d	2061.84 e	23.91 c	25.29 c
L59 x L77	1750.21 d	2150.25 e	27.94 a	26.17 c
L59 x L75	2634.36 c	2952.55 c	20.67 d	21.96 d
L59 x L80	1555.62 e	2081.99 e	26.90 b	27.02 b
P6 x L76	2615.98 c	2878.44 c	25.81 b	27.94 b
P6 x L77	2754.53 b	3006.07 c	27.61 a	28.81 b
P6 x L75	3862.42 a	3994.75 a	23.26 c	24.60 c
P6 x L80	2810.30 b	3113.48 b	29.33 a	29.67 a
L76 x L77	1203.27 e	1503.63 f	25.68 b	27.96 b
L76 x L75	2257.84 c	2555.88 d	25.68 b	23.75 c
L76 x L80	1206.70 e	1295.69 g	27.72 a	28.81 b
L77 x L75	2765.39 b	3103.30 b	26.53 b	24.62 c
L77 x L80	1792.40 d	2006.10 e	28.49 a	29.69 a
L75 x L80	2605.31 c	2933.74 c	26.31 b	25.48 c
Mean	2071.37	2315.44	25.77	26.56

Means followed by the same letter in a column belong to the same group by the Scott-Knott (1974) test, at 5% probability.

PERFORMANCE

In the environments with nutritional stress, the estimates of the experimental variation (CVe) coefficient were higher than in the unstressed environments, although in general, they were low for the traits RG, PE and VP, respectively (15.11%, 10.22% and 16.94% in Campos dos Goytacazes and 14.95%, 9.34% and 19.43% in Itaocara).

The mean grain yields of the hybrids UENF P01, UENF P02 and UENF P03 were 3.1, 3.2 and 3.1 t ha^{-1}, respectively, at optimal P availability and 3.0, 2.9 and 2.8 t ha^{-1}, in this order, at low soil P levels. In addition, the mean hybrid yields were higher than the experimental means in all environments (Table 2).

OTHER TRAITS

The hybrids UENF P01, UENF P02 and UENF P03 were evaluated based on agronomic and morphological traits, as proposed by the National Plant Variety Protection (SNPC) for registration by MAPA. Hybrid UENF P01 has yellow grain, a mean plant height of 2 m and mean ear height of 1.24 m. The popping expansion was 31.44 mL g^{-1} and grain yield 3,134.00 kg ha^{-1}.

Hybrid UENF P02 is a yellow grain cultivar, with a mean plant height of 2.02 m and a mean ear height of 1.11 m. The popping expansion was 30.00 mL g^{-1} and grain yield 3,213.00 kg ha^{-1}. The hybrid UENF P03 is also a yellow-grain cultivar, with a mean plant height of 1.95 m and a mean ear height of 1.17 m. The popping expansion was 30.10 mL g^{-1} and grain yield 3,113.00 kg ha^{-1} (Table 2).

MAINTENANCE AND BASIC SEED PRODUCTION

The hybrids UENF P01, UENF P02 and UENF P03 were registered by the Ministry of Agriculture, Livestock and Supply - MAPA, under the respective numbers 39248, 39249 and 39250. The State University of Northern Rio de Janeiro - UENF, together with the seed company Rio Norte Sementes, based in Campos dos Goytacazes, RJ, are in charge of the hybrid seed production and marketing.

ACKNOWLEDGMENTS

The authors wish to thank the Foundation Carlos Chagas Filho for Research Support of the State of Rio de Janeiro (FAPERJ) and the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES)/Funding Code 001.

REFERENCES

Albino-Schwantes I, Amaral Júnior AT, Almeida Filho JT, Santos PHAD, Ferreira FRA, Mafra GS, Vivas M, Souza YP, Oliveira FP, Gerhardt IFS and Santos JS (2020) Comparative analysis of bayesian and frequency-based methods in genomic selection for popcorn population breeding and optimization of SNP marker density. **Functional Plant Breeding Journal 1**: 61-72.

Almeida RN, Vivas M, Santos Junior DR, Saluci JCG, Carlos MC, Santos JS, Amaral Júnior AT and Scapim CA (2021) Combining abilities analysis for ear rot resistance in popcorn hybrids development. **Revista Ceres 68**: 61-70.

Amaral Júnior A, Poltronieri TPS, Santos PHD, Vivas M, Gerhardt IFS, Carvalho BM, Freitas CS and Silveira SF (2019) Reaction of popcorn lines (S_7) cultivated in distinct phosphorus levels to Bipolaris maydis infection. **Summa Phytopathologica 45**: 18-22.

Barros VMS, Martins LD, Rodrigues WN, Ferreira DS, Christo BF, Amaral JFT and Tomaz MA (2022) Combined doses of nitrogen and phosphorus in conilon coffee plants: changes in absorption, translocation and use in plant compartments. **Journal of Plant Nutrition 45**: 346-357.

Conceição-Silva T, Amaral Júnior AT, Almeida Filho JE, Freitas MSS, Guimarães AG and Kamphorst SH (2019) Contrasting phosphorus environments as indicators for popcorn breeding lines. **Functional Plant Breeding Journal 1**: 1-15.

Gerhardt IFS, Amaral Junior AT, Pena GP, Guimarães LJM, Lima VJ, Vivas M, Santos PHAD, Ferreira FRA, Freitas MSM and Kamphorst SH (2019) Genetic effects on the efficiency and responsiveness to phosphorus use in popcorn as estimated by diallel analysis. **Plos One 14**: e0216980.

Gerhardt IFS, Júnior ATA, Guimarães LJM, Schwantes IA, Santos A, Kamphorst SH, Lima VJ, Poblete FM and Myers GO (2017) Intraspecific variability of popcorn S_7 lines for phosphorus efficiency in the soil. **Genetics and Molecular Research 16**: 1-13.

Kamphorst SH, Amaral Júnior AT, Vergara-Diaz O, Gracia-Romero A, Fernandez-Gallego JA, Chang-Espino MC, Buchaillot ML, Rezzouk FZ, Lima VJ, Serret MD and Ortega JLA (2022) Heterosis and reciprocal effects for physiological and morphological traits of popcorn plants under different water conditions. **Agricultural Water Management 261**: 107371.

Khan S, Amaral Júnior AT, Ferreira FRA, Kamphorst SH, Gonçalves GMB, Freitas MMS, Silveira V, Souza Filho GA, Amaral JFT, Bresssan-Smith RF, Khalil IH, Vivas JMS, Souza YP and Peçanha DA (2020) Limited nitrogen and plant growth stages discriminate well nitrogen use, uptake and utilization efficiency in popcorn. **Plants 9**: 893.

Khan S, Pinto VB, Amaral Júnior AT, Gonçalves GMB, Corrêa CCG, Ferreira FRA, Souza GAR, Campostrini E, Freitas MSM, Vieira ME, Oliveira Santos T, Lima VJ, Kamphorst SH, Amaral JFT, Mora-Poblete F, Souza Filho GA and Silveira V (2022) Revealing the differential protein profiles behind the nitrogen use efficiency in popcorn (*Zea mays* var. everta). **Scientific Reports 12**: 1521.

Kurosawa RNF, Amaral Junior AT, Vivas M, Almeida RN, Vivas JMS, Lima VJ and Silveira SF (2021) Diallel analysis for resistance to northern leaf blight in popcorn under contrasting nitrogen availability. **Agronomy Journal 113**: 1029-1038.

Leite JT, Amaral Junior AT, Kamphorst SH, Lima VJ, Santos Junior DR, Alves UO, Azeredo VC, Pereira JL, Bispo RB, Schmidt KFM, Viana FN, Viana AP, Vieira HD, Ramos HCC, Ribeiro RM and Campostrini E (2022) All are in a drought, but some stand out: multivariate analysis in the selection of agronomic efficient popcorn genotypes. **Plants 11**: 2275.

Lima VJ, Amaral Júnior AT, Kamphorst SH, Santos A, Schmidt KFM, Azeredo VC, Leite JT, Santos Junior DR, Santos TO, Bispo RB, Carvalho CM, Souza YP, Oliveira FT, Chaves MM, Oliveira UA, Mafra GS and Santos PHAD (2021) UENF WS01: popcorn hybrid with water use efficiency for the State of Rio de Janeiro. **Crop Breeding and Applied Biotechnology 21**: 1-6.

Mafra GS, Amaral Júnior AT, Almeida Filho JE, Vivas M, Santos PHAD, Santos JS, Pena GF, Lima VJ, Kamphorst SH, Oliveira FT, Souza YP, Schwantes IA, Santos TO, Bispo RB, Maldonado C and Mora F (2019) SNP-based mixed model association of growth- and yield-related traits in popcorn. **Plos One 14**: e0218552.

MAPA - Ministério da Agricultura, Pecuária e Abastecimento (2020) Formulários para registro de cultivares. Available at <https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/sementes-e-mudas/registro-nacional-de-cultivares-2013-rnc-1/formularios-para-registro-de-cultivares>. Accessed on November 20, 2020.

March MD, Toma L, Stott AW and Roberts DJ (2016) Modelling phosphorus efficiency within diverse dairy farming systems – pollutant and non-renewable resource? **Ecological Indicators 69**: 667-676.

Santos A, Amaral Júnior AT, Kamphorst SH, Gonçalves GMB, Santos PHAD, Vivas JMS, Mafra GS, Khan S, Oliveira FT, Schmitt KFM, Santos Junior DR and Mora F (2020) evaluation of popcorn hybrids for nitrogen use efficiency and responsiveness. **Agronomy 10**: 485.

Santos JS, Souza YP, Vivas M, Amaral Júnior AT, Almeida Filho JE, Mafra GS, Viana AP, Gravina GA and Ferreira FRA (2020) Genetic merit of popcorn lines and hybrids for multiple foliar diseases and agronomic properties. **Functional Plant Breeding Journal 2**: 33-47.

Santos TO, Amaral Junior AT, Bispo RB, Lima VJ, Kamphorst SH, Leite JT, Santos Júnior DR, Santos PHAD, Oliveira UA, Schmitt KFM, Campostrini E, Moulin MM, Viana AP, Gravina GA, Corrêa CCG and Gonçalves GMB (2021) Phenotyping latin american open-pollinated varieties of popcorn for environments with low water availability. **Plants 10**: 1211.

Schmitt KFM, Lima VJ, Júnior ATA, Santos JS, Mafra GS, Vivas M, Kamphorst SH, Souza YP, Oliveira FT, Ferreira FRA and Vivas JMS (2019) Combining ability of popcorn lines for resistance to the fungus Puccinia polysora (Pucciniaceae). **Genetics and Molecular Research 18**: 1-11.

Scholz RW, Ulrich AE, Eilittä M and Roy A (2013) Sustainable use of phosphorus: A finite resource. **Science of the Total Environment 461-462**: 799-803.

Schwantes IA, Amaral Júnior AT, Almeida Filho JE, Vivas M, Cabral PDS, Guimarães AG, Lima e Silva FH, Santos PHAD, Pereira MG, Viana AO, Pena GF and Ferreira FRA (2020) Genomic selection helps accelerate popcorn population breeding. **Crop Science 60**: 1373-1385.

Schwantes IA, Amaral Júnior AT, Vivas M, Almeida Filho JE, Kamphorst SH, Guimarães AG and Khan S (2018) Inheritance of resistance to Fusarium ear rot in popcorn. **Crop Breeding and Applied Biotechnology 18**: 81-88.

Viana FN, Chaves MM, Kamphorst SH, Amaral Junior AT, Lima VJ, Leite JT, Schmidt KFM, Oliveira UA, Lamego DL, Pereira JL, Pena GF, Vieira HD, Oliveira JG, Daher RF, Campostrini E and Bressan-Smith R (2022) Heritability of morphophysiological traits in popcorn for drought tolerance and their use as breeding indicators of superior genotypes. **Agronomy 12**: 1517.

Zeng Q, Mei T, Delgado-Baquerizo M, Wang M and Tan W (2022) Suppressed phosphorus-mineralizing bacteria after three decades of fertilization. **Agriculture, Ecosystems & Environment 323**: 107679.