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BIOLOGY

Estimation of genetic merit of diallel hybrids of sweet pepper by mixed models

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ABSTRACT: *The use of mixed models for evaluating diallel crosses is a highly timely option to the reliable prediction of progeny genetic values. In the sweet pepper crop, hybrids are commercially explored on a large scale, mainly because of their characteristics of economic importance. This study aimed to assess the potential of hybrids obtained from a partial diallel among five sweet pepper lines developed for the hydroponic cultivation system and two simple hybrids, by applying mixed models. It was performed crosses in the partial diallel scheme among the (L1B, L6, L7, L18, and L19) lines and the simple hybrids 'Valdor' and 'Atlantis'. Plants were cultivated in hydroponic system with substrate and irrigated three times a day using nutrient solution. On the basis of mixed models, the following traits were assessed: mean fruit diameter (FD), mean fruit length (FL), mean fruit number per plant (FNP), mean fruit mass (FM), early yield (EYIELD), and mean fruit mass per plant (FMP). The L6 line was the one that showed the highest estimate of general combination capacity for FMP, FM, and EYIELD, proving to be promising for recommendation. The hybrid that provided the best specific combining ability for FD, FM, FMP, and EYIELD was L6 x 'Valdor'. Triple hybrids were efficient to maximize yield for the traits of interest by the use of the mixed model.*
Key words: *Capsicum annuum, combining ability, hydroponic cultivation, REML/BLUP.*

Estimação do mérito genético de híbridos dialélicos de pimentão sob cultivo hidropônico via modelos mistos

RESUMO: *A utilização de modelos mistos na avaliação de cruzamentos dialélicos é uma opção altamente oportuna para a fidedigna predição dos valores genéticos das progênies. Na cultura do pimentão, os híbridos são largamente explorados comercialmente, principalmente por suas características de importância econômica. O objetivo deste trabalho foi avaliar o potencial de híbridos resultantes de um dialelo parcial entre cinco linhagens de pimentão desenvolvidas para o sistema de cultivo hidropônico e dois híbridos simples, utilizando modelos mistos. Foram realizados cruzamentos no esquema de dialelo parcial entre as linhagens (L1B, L6, L7, L18 e L19) e os híbridos simples 'Valdor' e 'Atlantis'. As plantas foram cultivadas em sistema hidropônico com substrato e irrigadas três vezes ao dia com solução nutritiva. Com base em modelos mistos, foram avaliadas as características: diâmetro médio de frutos (DF); comprimento médio de frutos (CF); número médio de frutos por planta (NFP); massa média de frutos (MMF); produção precoce (PP) e massa média de frutos por planta (MFP). A linhagem L6 foi a que expressou maior estimativa de capacidade geral de combinação para MFP, MMF e PP, revelando-se promissora para recomendação. O híbrido triplo que apresentou melhor capacidade específica de combinação para DF, MMF, MFP e PP, foi L6 x 'Valdor'. Os híbridos triplos foram eficientes para incrementar a produtividade para as características de interesse com a aplicação da modelagem mista.*
Palavras-chave: *Capsicum annuum, capacidade geral de combinação, cultivo hidropônico, REML/BLUP.*

INTRODUCTION

Sweet pepper is one of the most important oleraceous grown and commercialized in Brazil and worldwide. In Brazil, about 290 thousand tons of fruits are yielded, mainly from São Paulo, Minas Gerais, Bahia, and Rio de Janeiro States (MAROUELLI & SILVA, 2012; CHEEMA et al., 2018).

The most recent cultivation system on the yield of colored sweet pepper is the one protected in hydroponic system. This system stimulates the yield of high quality fruits of lower costs on agricultural pesticides during cultivation, as color sweet pepper needs more time to mature in field; thus, it turns more susceptible to diseases. This cultivation system has become ever more an economically

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viable market niche, besides keeping the supply of the product throughout the year with yields of more than 3 kg per plant (FU et al., 2018). CHARLO et al. (2009) stated that bout sweet pepper hybrids in a protected environment with hydroponic system are still scarce. Hence, assessing traits of sweet pepper hybrids for this system is essential. RUBIO et al. (2010) also emphasized that the use of hydroponic system increments the response of the cultivars, as it increases the efficiency of water and nutrients use. Thus, it is vital to find cultivars that provide superior yield responses under this system.

The current strategy to develop superior cultivars has been based on the obtention of hybrids that prove their quality and superior traits in terms of the performance of genitor line. Nevertheless, this strategy can also be used to form a population-base, that is, the selection of the best lines or crosses of double or triple hybrids, according to the estimates of general and specific combining ability (MARCHESAN et al., 2009).

Many researches have been conducted with diallels to estimate the general combining ability (GCA) and the specific combining ability (SCA), based on genetic parameters obtained from the traits of interest, such as in the tomato crop with complete diallel without reciprocal (AMARAL JÚNIOR et al., 2017), zucchini crop with partial diallel (NOGUEIRA, 2011), pepper crop with partial diallel (SHUELTER et al., 2010), and sweet pepper crop with complete diallel (PECH MAY et al., 2010; DEMIDOV et al., 2017).

The diallel crossing system with analysis by mixed models distinguishes itself as a very robust predictor for the estimates of the progeny variance component, once it provides the estimates of the hybrid crosses that were not carried out by the pedigree information of the genitors (RODRIGUES et al., 2017).

The mixed models approach allowed accurate predicting genetic effects, even unbalanced data. Therefore, the mixed models equation allowed estimation of the fixed effects and predicting the random effects. In this research mixed models can pedigree information of hybrids and help i to select superior combinations (PÁDUA et al., 2016).

Given that, the goal of this research was to predict the potential of hybrids using the combining ability of a partial diallel by means of mixed models among five lines of sweet pepper developed for the protected cultivation system in hydroponic medium and two simple hybrids.

MATERIALS AND METHODS

The experiment was realized in 2014 at Recife City, Pernambuco State, Brazil. According to the classification climate of Köppen, the climate of Recife is (As’) hot humid tropical with autumn-winter rains. Five lines of sweet pepper of the solanaceous breeding program for the hydroponic cultivation system (L1B, L6, L7, L18 e L19) of the Universidade Federal Rural de Pernambuco – UFRPE were crosses, in a partial diallel scheme with two simple hybrids, specifically ‘Atlantis’ and ‘Valdor’. Triple hybrids were grown at a greenhouse of the Agronomy Department of the UFRPE. The lines presented square-shaped fruits, thick pulp, precocity, and red fruits, excepting L6 line, which presented yellow fruits. Hybrids used for crosses were chosen due to presenting different morphological fruit and yield traits, such as rectangle shape of fruit, elongated fruit shape, and high yield per plant.

The L1B, L6, L7, L18, and L19 lines were applied as female genitors and the ‘Atlantis’ and ‘Valdor’ hybrids, as male genitors, following a partial diallel scheme among the five lines and the two hybrids, which resulted in ten triple hybrids (L1B x ATL, L1B x VAL, L6 x ATL, L6 x VAL, L7 x ATL, L7 x VAL, L18 x ATL, L18 x VAL, L19 x ATL, and L19 x VAL), which were assessed in this test together with four sweet pepper cultivars, as control, namely, ‘All Big’, ‘Paloma’, ‘Impacto’, and ‘Rubia’.

The experiment was conducted applying a randomized block experimental design, comprising 21 treatments, each one composed of five lines, two simple hybrids, ten triple hybrids, and four control cultivars. Each plot was composed of four plants arranged in 1,75 m spacing between rows and 0,60 m between plants.

Seeding was carried out on 128-cell expanded polystyrene trays with commercial substrate. Seedlings were transplanted to 5 L pots filled with substrate 35 days after sowing. The plants were cultivated in a hydroponic system with substrate and watered three times a day using a nutrient solution in accordance with the needs of the crop for each development growth stage by means of a pressurized drip system. To this end, a nutrient solution was applied up to achieving the pot capacity and starting the leaching, at the time the irrigation was immediately stopped.

Adapted from FURLANI et al. (1999), the nutrition solution was chosen for the cultivation of sweet pepper. To prepare 1,000 L of the pre-flowering solution, 750 g of calcium nitrate, 450 g of potassium nitrate, 200 g of monoammonium phosphate (MP), 400 g of magnesium sulphate, 25 g of iron chelate – EDDHA-Fe –, and 25 g of solid micronutrient mixtures chelated by EDTA were used. For the fruiting solution, the same fertilizers were used with their respective dosages with addition of boric acid (diluted 25 g of the solid product in 1 L of water and using 75 mL of this solution in 1,000L) and 150 g of monopotassium phosphate (MKP).

Plants were pruned to the 1-2-4 system, remaining with four branches until the end of the cycle (FINGER & SILVA, 2005). The first flower, at the first fork, was removed. To keep the plants upright to avoid their fall, the plant tutoring was performed using a central string installed from the base of the plant to its apex. Simultaneously, two strips were passed on the sides of the plants while developing. Fruits were harvested when they began to change color, which indicated the start of the physiological maturation, aiming to standardize the end of their development.

The agronomic traits assessed were fruit diameter (FD), fruit length (FL), mean fruit number per plant (FNP), mean fruit mass (FM), early yield (EYIELD) (it corresponds to the yield obtained in the first three harvests), and mean fruit mass per plant (MFP). Mean data of the four plants were used in the plots of each treatment for the six traits assessed, given that, in the whole experiment, nine harvests were carried out.

The statistical model applied was the GRIFFING (1956) Model 1: Y = Mc + Gi + Gj + Sij + E, in which Mc is the mean of all individuals in crosses, Gi and Gj are the effects of the general combining ability of the individuals i and j, respectively. In the prediction of the mixed model, the following expression was adopted: yij = uc + ai + aj + dij + e by means of the Selegen-REML/BLUP software (RESENDE, 2016), in which **a** refers to the additive genetic effect and d, to the dominance genetic effect associated with the ij family.

The model utilized was $y = X_r + Z_+ W_s + T_p + e$, at where y is vector of data, r is vector of block effects (assumed to be fixed), g is the vector of effects of general combining ability of the parents involved in the crosses (assumed to be random), s is the vector of specific ability combining of parental and lines, p is the vector of plot effects and e is the random errors.

The variance distributions and structures related to the models terms are:

$$y|r,V \sim N(Xr,V)$$
$$g|I\sigma^2_g \sim N(0,I\sigma^2_g)$$
$$s|\sigma^2_s \sim N(0,I\sigma^2_s)$$
$$p|\sigma^2_p \sim N(0,I\sigma^2_p)$$
$$e|\sigma^2_e \sim N(0,I\sigma^2_e)$$
$$V = Z\sigma^2_g Z' + W\sigma^2_s W' + TI\sigma^2_p T' + I\sigma^2_e$$

The estimates of genetic parameters were realized by the current expressions:

General Combining Ability: $\hat{c}^2_g = \frac{\hat{\sigma}^2_g}{\hat{\sigma}^2_y}$;

Specific Combining Ability: $\hat{s}^2_g = \frac{\hat{\sigma}^2_s}{\hat{\sigma}^2_y}$;

RESULTS AND DISCUSSION

Estimates of genetic parameters by REML

By analyzing the genetic variances between the male genitors and the lines, the variability between the simple hybrids can be seen with regard to the FL (29.42), FMP (0.22), and FM (645.3) traits; in turn, for the lines, the traits with the greatest variabilities were FD (11.45) and FNP (2.94). These results are explained because the male genitors (simple hybrids) have a larger fruit length and the lines, a greater fruit diameter.

In all the traits assessed, there was superiority of the additive action regarding the dominance effects in the genetic variance (Va + Vd), as it was with the significant effect of FL (50.23), FD (11.46), FMP (0.37), FM (1195.32), FNP (3.2), and YIELD (0.02) (Table 1). Similarly, YADAHALLI et al. (2017) reported higher effects of the additive action for the mean fruit mass and fruit length traits, assessing 30 hybrids of sweet pepper in complete diallel.

One of the most important traits in the yield sweet pepper is the fruit mass, in which the overall mean was 3 Kg. This being the case, one of the specificities of the crop is that its harvests generate costs of labor and inputs – such as pesticides, and as such, early yield is essential, as it is related to the yield of the first three harvests, which are in charge of 45.33 of the total yield, whose phenotypic expression was inherited from the genitor lines.

In accordance with XAVIER et al. (2016), a selection is highly favored by the relation between the coefficient of genotypic variation and the coefficient of environmental variation, for which values of 1.0 or higher prove that the genetic variation is superior to the environmental one.

In this research, this higher relation was reported for the mean mass fruit (1.86) trait, showing the dominance of FM in obtaining gains by selection. Similarly, the other traits expressed FMP (1.31), FD (0.96), FL (0.89), EYIELD (0.81) and FNP (0.63) (Table 1), which means that the selection based on

Table 1 - Restricted maximum likelihood (REML) estimates of variance components in the traits of sweet pepper of a partial diallel assessed in a protected environment in hydroponic system.

Variance components (Individual REML)	FL	FD	FMP	FM	FNP	EYIELD
Genetic variance among male genitors	29.42	0.01	0.22	645.30	0.25	0.01
Genetic variance among female genitors	20.81	11.45	0.15	550.01	2.94	0.01
Mean additive genetic variance	50.23	11.46	0.37	1195.32	3.20	0.02
Dominance genetic variance (SCA)	0.46	0.04	0.01	277.16	0.06	0.00
Residual variance	63.71	12.40	0.22	422.92	7.97	0.02
Individual phenotypic variance	114.42	23.91	0.60	1895.41	11.23	0.04
Individual narrow-sense heritability (M)	0.64	0.02	0.76	0.73	0.19	0.39
Individual narrow-sense heritability (F)	0.36	0.95	0.49	0.58	0.52	0.61
Determining coefficient of effects (SCA)	0.00	0.01	0.02	0.14	0.01	0.01
Individual heritability of interpopulation dominance effects	0.00	0.01	0.02	0.14	0.01	0.01
Individual narrow-sense heritability (MF)	0.44	0.48	0.63	0.77	0.29	0.40
Individual broad-sense heritability	0.43	0.47	0.61	0.63	0.28	0.39
Genotypic variance coefficient among progenies	7.63	4.35	20.63	29.73	7.59	9.64
Residual variance coefficient	8.56	4.51	15.68	15.93	11.87	11.88
Overall mean	93.24	77.95	3.00	129.05	23.78	1.36

Mean fruit diameter (FD), mean fruit length (FL), mean fruit number per plant (FNP), mean fruit mass (FM), early yield (EYIELD), and mean fruit mass per plant (FMP).

these traits will have gains relative to the genotype proportion previously *mentioned.*

Estimates of general combining ability

For the FNP trait, two lines presented estimated values higher than 1.0 – L1B and L7 -; the others showed values lower than 0.5 or negative values. For FMP, there were two genotypes with positive values, which were: L6 line (>0.5) and 'Valdor' male genitor (<0.5). Three genotypes reported positive values for EYIELD, specifically: 'Valdor' male genitor (>0.0), L6 line (>0,0), and L19 line (>0.0). In this way, the L6 female genitor was the one that contributed the most to increase the mean fruit mass, as, for this set of traits, despite this line does not provide a good estimate of general combining ability for fruit number per plant (>-1.0), they are longer and with a larger diameter. As a result, they have the highest mean fruit mass (>30), that is, despite yielding few fruits, they present the highest mean mass compared to the other genotypes, which is of significant commercial interest (Figure 1).

With regard to the FD, FL, and FM traits, related to the male genitors, only 'Valdor' displayed a positive contribution for FL (>3 mm) and FM (>10 g). Among the female genitors, only L6, L18, and L19 lines showed positive results, with L6 being the one that expressed the possibility of gain for the three traits – FD (>3 mm), FL (>4 mm), and FM (>30 g). DEVI et al. (2018), when assessing 29 genotypes of *Capsicum annuum* L. var. *grossum* Sendt., reported positive values of general combining ability for fruit number per plant, concluding that the Sel-1, DARL-10 e UHFSP(Y)-11 lines were the most promising for the increase of fruit yield per plant based on its general combining ability.

Estimates of specific combining ability

For FD, the L6 x ATL hybrid cross had the highest specific combining ability (0.017 mm) and the highest genetic value (81.46), which can be explained by the good allelic complementation of the L6 and 'Atlantis' genitors for this trait (Table 2).

The highest specific combining ability for fruit length was for the L19 x VAL (0.16) hybrid; however, the highest genetic combining value (100.11 mm) was given by the L6 x ATL cross.

For FM, the highest specific combining ability (23.73) and the genetic value (203.92 g) occurred for the L6 x VAL cross, which proves a high genetic contribution of these genitors for the increase of the fruit mass GANEFIANTI & FAHRURROZI (2018) proved that the FL, FD, FNP, and FMP traits were affected by additive genetic actions, mainly, as a result of the genetic control and the allelic complementation of the genotypes.

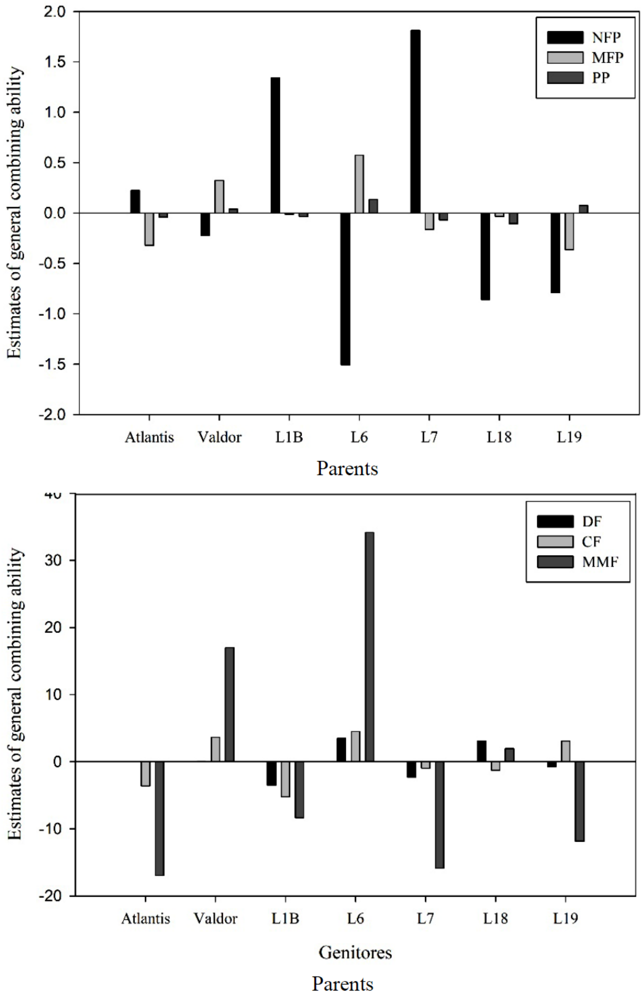

Figure 1 - Estimates of general combining ability (CGC) of the mean fruit diameter (FD), mean fruit length (FL), mean fruit number per plant (FNP), mean fruit mass (FM), early yield (YIELD), and mean fruit mass per plant (FMP).

As regards the FNP, the most significant estimate of the specific combining ability was for the L6 x ATL cross (0.04); and the highest genetic value, for the L7 x ATL cross (25.83). The genitors which contributed the most increasing the FNP were ATL and L7. For its part, for FMP, the L1B x ATL (0,05) hybrid provided the highest estimate of *Sij*, while L6 x VAL was superior for the genotypic value, with a mean of 3.94 kg plant-[1]. Lastly, concerning EYIELD, the most expressive estimate of *sij*, as well as the genetic value of the cross happened with the L6 x VAL hybrid, given by the respective values 0.0019 and 1.5338. To increase the FMP and EYIELD, the VAL and L6 genitors showed better contribution in the estimates for yield and mean fruit mass increment. These estimates indicate the producer that the L6 line is a potential line for yield of triple hybrids, since it presents traits of increment in the amount of fruit, mean mass, and in its precocity.

Therefore, besides confirming the good performance of the L6 line for general combining ability, it is important to compare the predicted genetic values of the L6 x VAL (yellow) and L6 x ATL (red) hybrids. By analyzing these values, the L6 x VAL cross was the one with the most desirables attributes for yield and commercialization of

Table 2 - Estimates of specific combining ability (SCA), genotypic value of the cross (VGC) and ranking of hybrid combinations (R) for the color characteristics of the fruit (COLOR), fruit diameter (FD), fruit length (FL), mean fruit number per plant (FNP), mean fruit mass (FM), early yield (EYIELD) and mean fruit mass per plant (MFP) of a partial diallel of sweet pepper evaluated in protected environment in hydroponic system.

Hybrids	Color (Fruit)	----------FD (mm)-------			-----------------FL (mm)----------------			--------------------FM (g)-----------------		
		SCA	VGC	R	SCA	VGC	R	SCA	VGC	R
L1B x ATL	Red	0.002	74.43	10	-0.09	84.26	10	9.13	112.84	7
L6 x ATL	Red	0.017	81.46	1	0.08	100.11	1	-6.52	139.69	3
L7 x ATL	Red	-0.010	75.61	8	0.03	95.84	2	-1.33	94.88	10
L18 x ATL	Red	0.002	81.07	4	0.01	95.52	3	-6.48	107.52	8
L19 x ATL	Red	-0.014	77.17	6	-0.09	91.61	6	-2.07	98.13	9
L1B x VAL	Red	-0.015	74.41	9	-0.02	92.58	5	-13.34	124.32	5
L6 x VAL	Yellow	-0.003	81.44	2	0.01	88.30	8	23.73	203.92	1
L7 x VAL	Red	0.001	75.62	7	-0.05	88.65	7	-6.65	123.52	6
L18 x VAL	Red	0.009	81.07	3	-0.04	94.17	4	7.46	155.43	2
L19 x VAL	Yellow	0.011	77.20	5	0.16	84.26	9	-3.89	130.27	4
Hybrids	Color (Fruit)	------------FNP-----------			-------------MFP (kg plant^{-1})-----------			----------EYIELD (Kg plant^{-1})----------		
		SCA	VGC	R	SCA	VGC	R	SCA	VGC	R
L1B x ATL	Red	0.01	25.36	3	0.05	2.719	6	-0.0012	1.281	8
L6 x ATL	Red	0.04	22.54	9	-0.00	3.251	10	-0.0005	1.453	3
L7 x ATL	Red	0.01	25.83	1	-0.00	2.510	8	-0.0009	1.248	9
L18 x ATL	Red	0.01	23.15	6	-0.03	2.609	7	-0.0001	1.213	10
L19 x ATL	Red	-0.02	23.19	5	-0.02	2.288	9	0.0014	1.396	4
L1B x VAL	Red	0.01	24.91	4	-0.05	3.261	2	0.0008	1.361	5
L6 x VAL	Yellow	-0.07	21.98	10	0.04	3.947	1	0.0019	1.534	1
L7 x VAL	Red	0.02	25.39	2	-0.00	3.155	4	0.0002	1.328	6
L18 x VAL	Red	-0.02	22.67	8	0.03	3.321	3	-0.0010	1.290	7
L19 x VAL	Yellow	0.00	22.78	7	-0.00	2.956	5	-0.0006	1.472	2

yellow sweet peppers, such as FD, FM, FMP, and EYIELD. Nevertheless, depending of the goal and the color of the fruit, the yellow fruit hybrid should be recommended, as it has the highest market value, or the hybrid of red fruit, since it has a higher value than the green fruit,;although, slightly lower value than the yellow one. The choice made by the L6 x VAL triple hybrid was, especially, due to the high values of specific ability, which were superior in up to three times the other crosses for the mean fruit mass trait, which is essential to increase yield and unit value of the product, besides the possibility of combining in a single triple hybrid quantitative and qualitative attributes of interest for launching as a new colored fruit cultivar, what is ensured by the elevated estimates of the general abilities of the genitors involved (Gomide et al., 2008).

Regarding (SANTOS, 2017), hybrids distinguished as supremacy in this research (L6 x Valdor and L6 x Atlantis) were superior than triple hybrid L1B x Valdor. Therefore, it was not only a higher expectation of vigor through analysis of mixed modeling, but also the insertion of a characteristic of supreme importance for the ideotype selection of chili genotypes brought greater evolution in the conception of the results.

CONCLUSION

The additive genetic effects contributed to the increase in all evaluated characteristics, especially fruit mass and length.

The simple hybrids ‘Atlantis’ and ‘Valdor’ showed higher general ability of combination, offering suitable gains by the selection of genetically superior individuals over segregating generations and establishing a base population.

The most promising triple hybrids, concerning the traits assessed for hydroponic cultivation, is the hybrid of yellow fruit L6 x ‘Valdor’ (3,947 kg/plant) and the hybrid of red fruit L6 x ‘Atlantis’ (3,251 kg/plant).

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DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS’ CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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Erratum

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