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Scientific Article

Agronomic performance of grain amaranth in the semi-arid region as a function of the planting arrangement

Desempenho agronômico do amaranto no semiárido em função do arranjo espacial

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ABSTRACT - The potential effects of climate change on agricultural yields require a greater understanding of cropping systems that include underutilized agricultural crops with greater adaptive capacity to water and thermal stresses, such as grain amaranth (*Amaranthus* sp.). The aim of this work was to evaluate how the planting arrangement affects the agronomic performance of grain amaranth BRS Alegria (*Amaranthus cruentus* L.) grown under semi-arid conditions. One experiment was carried out in a complete randomized block design with five repetitions in a 2 x 3 factorial scheme (two row spacings - 30 and 40 cm; three plant spacings - 20; 30 and 40 cm); in two crop years, 2019 and 2020 in the municipality of Pentecoste, CE, Brazil. The evaluated characteristics were plant height, stem diameter, number of leaves, fresh matter yield, aboveground biomass yield (dry weight), grain yield, thousand-grain weight, lipid content, and harvest and lodging indexes. The evaluated planting arrangements did not affect plant height and number of leaves, but did affect stem diameter and lodging index, as the 40 cm plant spacing resulted in greater stem diameter and lower lodging index. Narrow spacing (30 x 20 cm) resulted in a higher lodging index but also resulted in a higher fresh matter yield, aboveground biomass, grain yield, harvest index and lipid content. Thousand-grain weight was greater at 30 x 40 cm spacing. The 30 x 20 cm arrangement can be recommended for the cultivation of grain amaranth in the study area.

Keywords: *Amaranthus cruentus* L. Adaptability. Functional foods. Plant morphology. Yield.

RESUMO - Os potenciais efeitos das mudanças climáticas sobre a produção agrícola requerem maior compreensão dos sistemas agrícolas que incluem culturas subutilizadas com maior capacidade de adaptação a estresses hídricos e térmicos, como o amaranto (*Amaranthus* sp.). O objetivo deste trabalho foi avaliar como os arranjos espaciais afetam o desempenho agronômico do amaranto BRS Alegria (*Amaranthus cruentus* L.) no semiárido. Um experimento foi conduzido em delineamento de blocos casualizados com cinco repetições em esquema fatorial 2 x 3 (dois espaçamentos entre linhas - 30 e 40 cm; três espaçamentos entre plantas - 20; 30 e 40 cm); nos anos 2019 e 2020, no município de Pentecoste-CE. As características avaliadas foram altura da planta, diâmetro do caule, número de folhas, rendimento de matéria fresca, matéria seca, produtividade, peso de mil grãos, teor de lipídios nos grãos, índices de colheita e acamamento. Os arranjos espaciais não afetaram a altura das plantas e o número de folhas, mas afetaram o diâmetro do caule e índice de acamamento e o espaçamento de 40 cm entre plantas resultou em um maior diâmetro do caule e menor índice de acamamento. O espaçamento mais estreito (30 x 20 cm) resultou em maior índice de acamamento, porém também resultou em maior teor de matéria fresca, matéria seca, produtividade, índice de colheita e teor de lipídios. O peso de mil grãos foi maior no espaçamento 30 x 40 cm. O arranjo espacial 30 x 20 cm pode ser recomendado para o cultivo do amaranto na área de estudo.

Palavras-chave: *Amaranthus cruentus* L. Adaptabilidade. Alimentos funcionais. Morfologia da planta. Rendimento.

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INTRODUCTION

The potential effects of climate change on global agricultural production, such as yield losses, desertification, erosion, loss of water quality and water scarcity, have been reported as threats to guaranteeing global food security in the future, mainly in areas in which agriculture is climate sensitive, such as the arid and semi-arid regions (MAYES et al., 2012). Besides that, the rise in global population as well as the increase in energy costs and subsequent rise in the cost of agricultural inputs will sum up to the challenges in guaranteeing global food security in a climate change scenario (FUJIMORI et al., 2019).

The recommended strategies to adapt to those conditions include the adoption of diversified cropping systems that include crops that are tolerant to both water and heat stresses (BRASIL, 2016; LASCO; DELFINO; ESPALDON, 2014). According to Spehar (2007), the diversification of the cropping systems will rely on species with fast growth, water stress tolerance, satisfactory biomass yield, efficient nutrient uptake, and potential for use for both human and animal consumption.

Grain amaranth (*Amaranthus* sp.) stands out since it is well adapted to marginal lands and holds a significant potential for a bigger development due to its high genetic diversity and phenotypic plasticity (RASTOGI; SHUKLA, 2013). It also has an inherent tolerance to high temperatures, drought, and nutrient-poor soils, besides a lack of phytosanitary issues, which render grain amaranth a valuable crop to be cultivated under adverse conditions (FUENTES-REYES; CHÁVEZ-SERVÍN; GONZÁLEZ-CORIA, 2018).

Besides the adaptive characteristics of grain amaranth, this pseudo-cereal (i.e. a plant that produces grains but is not a grass) also stands out because of its nutritional value (COELHO et al., 2018). The main characteristics of this species include the high protein content (15-18%), as well as the lysine and calcium contents, with averages of 5.2 and 0.37 g 100 g^{-1} of dry matter, respectively (BRESSANI, 2018). In terms of utilization, this species can be used in both animal and human nutrition, and both the grains and the leaves can be consumed (SPEHAR; TEIXEIRA; LARA, 2003). The grain can be consumed fresh or processed into a flour that can be used for baking, although in certain parts of the South American continent it can be found being used in cereal bars, beverages, porridges, etc. (MAZZINI, 2019).

Concerning the spacing recommendations for the cultivation of this crop in Brazil, for the Cerrado region, Ferreira et al. (2014) observed that the dry matter content and the weight of the inflorescence and the grains had better responses when cultivated under high planting densities, while plant height, inflorescence length and width and stem diameter tend to be negatively affected by high density. Pittelkow et al. (2019) reported that, for the Brazilian Midwest, the population density with the highest production potential of *A. cruentus* L. *BRS Alegria* cultivar is between 228,000 and 242,000 pl ha^{-1}. Also, for the Brazilian Midwest, Guimarães (2013) reports that the recommended density for cultivars of *Amaranthus hypochondriacus* and *Amaranthus cruentus* L. is between 300,000 and 400,000 plants ha^{-1}, ideal both for high yields (above 1 t ha^{-1}) and good crop management. In synthesis, the recommendations concerning the optimal planting arrangement and density for amaranth have diverged significantly in the scientific literature, and the amount of data that has been published concerning grain amaranth's response to planting densities specifically in the Brazilian semi-arid region is non-existing.

Given the lack of information regarding the effects of the planting arrangements (row x plant spacing) of grain amaranth in the Brazilian semi-arid region, one field experiment was carried out in two cycles, aiming to evaluate how the interaction between the aforementioned factors affects the agronomic performance of *A. cruentus* BRS Alegria cultivar.

MATERIALS AND METHODS

Study Area

The experiment was carried out at the Vale do Curu Experimental Farm - FEVC (3.82°S; 39.34°W), belonging to the Federal University of Ceará, in the Pentecoste municipality, Ceará State, Brazil, in two cycles, during the dry season: the first from September through December 2019 and the second from October 2020 through January 2021. The soil of the area is classified as *Planossolo Háplico Eutrófico Solódico* (Albaquults) (EMBRAPA, 2013). According to Köppen's classification the climate in the region is BSw'h' (hot and dry semi-arid).

The environmental characteristics of the study area during the experimental period are displayed in Table 1.

Table 1. Environmental data from the study area during the experimental period. Pentecoste, CE, Brazil, 2019 - 2020.

Year	Month	Maximum Temperature (°C)	Minimum Temperature (°C)	Average Temperature (°C)	Rh%	Rainfall (mm)	Evaporation (mm)
2019	September	37.93	23.80	30.86	52.35	0.0	168.4
	October	38.93	23.04	30.98	50.32	0.0	208.4
	November	39.00	23.65	31.33	48.75	0.0	207.2
	December	38.64	24.05	31.34	51.63	5.8	177.4
2020	October	39.34	22.87	31.10	46.48	0.0	183.5
	November	38.66	24.14	31.40	55.90	0.0	210.1
	December	38.59	23.89	31.24	58.45	0.0	262.7
2021	January	37.30	24.48	30.89	61.71	11.0	235.3

Source: Vale do Curu Experimental Farm Meteorological Station, Pentecoste, CE, Brazil.
Rh% = Air relative humidity.

Treatments and experimental design

The experiment was carried out in a randomized complete block design in a factorial scheme with six treatments and five replications, making up for 30 plots (Table 2). The treatments consisted of combinations of row (30 and 40 cm) and plant spacings (20, 30 and 40 cm) that produced planting densities ranging from 62,500 to 166,666 plants ha^{-1}.

The total experimental area was 500 m². Each experimental unit consisted of a 1.2 to 1.6 m wide plot (varying according to each treatment) and 6.0 m length, with five rows. The three central rows of each plot were considered as usable area.

Table 2. Evaluated row and plant spacings and their resulting plant densities.

Row spacing (cm)	Plant spacing (cm)	Plant density (pl ha^{-1})
	40	83,333
30	30	111,111
	20	166,666
	40	62,500
40	30	83,333
	20	125,000

Experimental set up

Soil tillage consisted of weeding and incorporation of cattle manure to the soil to a proportion of 30 t ha^{-1}, aiming to standardize the experimental area and to increment the organic matter content in the soil, according to the recommendation by Costa and Lima (2010). Soil tillage and manure incorporation were performed manually using a hoe.

Soil and irrigation water samples were collected from the experimental area for analysis prior to the establishment of the experiments. Results are displayed in Table 3 and Table 4.

Table 3. Water analysis results.

Cations (mmol$_c$ L^{-1})					Anions (mmol$_c$ L^{-1})								2019
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Sum	Cl^{-}	SO_4^{2-}	HCO_{3-}	CO_3^{2-}	Sum	EC (dS m^{-1})	SAR	pH	Total dissolved solids (mg L^{-1})
5.6	4	8.6	0.1	18.3	12.8	--	4.8	--	17.6	1.72	2.77	6.9	1,101
Cations --------------(mmol$_c$ L^{-1}) --------------					Anions ------------------- (mmol$_c$ L^{-1}) -------------------								2020
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Sum	Cl^{-}	SO_4^{2-}	HCO_3^{-}	CO_3^{2-}	Sum	EC (dS m^{-1})	SAR	pH	Total dissolved solids (mg L^{-1})
8.8	5.8	3.81	0.44	18.8	13.5	--	5.56	--	19.06	1.86	1.00	6.9	1,190

Note: EC= electric conductivity; SAR= sodium adsorption ratio.

Table 4. Soil chemical analysis results.

						2019
pH (water)	EC dS m^{-1}	P[1] mg kg^{-1}	K^{+}	Na^{+}	Ca^{2+}	Mg^{+2}
			----------------------------------Cmol$_c$ kg^{-1}----------------------------------			
7.5	0.18	8	0.13	0.03	1.8	0.9
						2020
pH (water)	EC dS m^{-1}	P[1] mg kg^{-1}	K^{+}	Na^{+}	Ca^{2+}	Mg^{+2}
			----------------------------------Cmol$_c$ kg^{-1}----------------------------------			
7.6	1.93	21	0.06	0.77	4.2	0.9

Note: EC= electric conductivity.
[1]Mehlich extractant.

The seeds were manually sown in plastic trays containing 200 cells each, using up to four seeds per cell, sown no deeper than 2 cm, according to the recommendation by Santos et al. (2019). This approach was used in this study to ensure that the plant spacings were correctly arranged in the field. Since amaranth seeds are minute (roughly 1 – 1.5 mm diameter) and no machinery was available, achieving the aimed densities by sowing manually would be difficult, so transplanting was preferred.

The substrate consisted of a mixture of organic compost and coconut powder at a 1:1 v/v proportion. Transplantation of the seedlings from the trays to the field was performed 21 days after sowing (DAS), when the plants had four fully expanded leaves. 15 days after transplantation (DAT), harrowing was performed aiming to leave one single plant per hole.

Besides the incorporation of organic fertilizer (cattle manure), weekly foliar fertilization was performed using the

Greenleaf® soluble fertilizer, which contains both macro and micronutrients. The NPK 20:20:20 formulation [(20% total nitrogen N: 5.9% nitrate nitrogen + 3.9% ammoniacal nitrogen + 10.2% urea nitrogen), 20% available phosphoric acid (P_2O_5) (8.7% soluble phosphorus), 20% soluble potassium (K_2O) (16.6% soluble potassium), 0% calcium (Ca), 0% magnesium (Mg), 0.100% chelated iron (actual) (Fe), 0.050% chelated manganese (actual) (Mn), 0.050% chelated zinc (actual) (Zn), 0.050% chelated copper (actual) (Cu), 0.020% boron (actual) (B), 0.0005% molybdenum (actual) (Mo), 1.24% EDTA (chelating agent)] was used during the first 15 DAT, and the 12:48:8 formulation [(12% total nitrogen: 2.4% nitric nitrogen + 9.6% ammoniacal nitrogen), 48% phosphorus (P_2O_5), 8% potassium (K_2O), 0.0251% magnesium (Mg), 0.02% boron (B), 0.05% copper (Cu), 0.10% iron (Fe), 0.05% manganese (Mn), 0.0005% molybdenum (Mo) and 0.05% zinc (Zn)] was used during the remainder of the cycle, based on the recommendation for the quinoa crop by Oliveira Filho et al. (2018). A total of 10 fertilization events were carried out.

The fertilizer was sprayed using a 20 L backpack sprayer, following the recommendations for cereal production (200 g 100 L^{-1} of water), during the cooler hours of the day (early morning or evening). The change in the fertilizer formulation at 15 DAT aimed to stimulate flowering and to reduce vegetative growth by increasing the P contents and decreasing N and K contents (OLIVEIRA FILHO et al., 2018).

The irrigation system was micro sprinkler with daily irrigation concentrated in the morning. The irrigation depth was approximately 655 mm. When necessary, weeding was manually performed.

Harvest was performed when the inflorescences were physiologically mature, which is characterized by the easy detachment of the grains from the panicle when pressed between the fingers, which occurred around 70 DAT (~90 DAS) (SPEHAR; TEIXEIRA; LARA, 2003). Plant collection for biomass analysis was performed 15 days before grain harvest.

Evaluated characteristics

For the growth evaluation, three plants per plot were measured at the end of the crop's cycle (55 days after transplantation) but before grain harvest. The evaluated characteristics were:

Plant height (cm): Measured using a metric tape. Each plant was measured from the ground level to the topmost node.

Stem diameter (mm): Measured using a digital caliper at the ground level.

Number of leaves per plant.

Concerning biomass, the plant was divided into stems, leaves and inflorescences, and weighed to obtain the plant's fresh matter yield (t ha^{-1}). After that, those plants were placed in a forced air oven at 65 °C and kept until reaching constant weight, then the samples were weighed and the aboveground biomass (dry weight) (t ha^{-1}) was calculated.

Regarding the yield characteristics, a sample of ten inflorescences per plot was harvested and, after processing, the grains were weighed to determine the grain yield (t ha^{-1}) and the thousand-grain weight (g). The harvest index (%) was calculated using Equation 1:

$$\left(\frac{GW}{WPDW}\right) x\ 100 \quad (1)$$

In which:
GW = Grain weight
WPDW = Whole plant (stem, leaves and panicles) dry weight

Plant lodging was evaluated by means of an index, using the methodology described by Silva et al. (2019a) (Equation 2):

$$PLI = \frac{h\ x\ IW}{d\ x\ SW} \quad (2)$$

In which:
PLI = Plant lodging index (dimensionless);
h = Plant height (mm);
IW = Inflorescence fresh weight (g);
d = Stem diameter (mm);
SW = Stem fresh weight (g).

The lipid content in the grain was determined using the Soxhlet method (IAL, 2008), using the Tecnal TE-044® device. Hexane was used as solvent and the results were calculated considering the dry weight percentage.

Statistical analysis

The data were subjected to normality and homogeneity tests. Because each crop cycle was planted on different planting dates, and therefore the plants were subject to different environmental conditions in each cycle, the analysis of variance was performed separately for each crop cycle and the different cycles (2019 and 2020) were not considered as a factor. Whenever significant (p<0.05), the means were compared by the Tukey test at 5% probability level, using the SISVAR® statistical software (FERREIRA, 2019).

RESULTS AND DISCUSSION

Growth

Among the evaluated growth characteristics, only stem diameter and lodging index were significantly affected by the planting arrangements (p<0.05) (Table 5), the first was affected by the plant spacing and the latter by row and plant spacing, both in the first year. In the second cycle, stem diameter was on average 18.11 mm and the lodging index was on average 18.84. Plant height was on average 159.64 and 148.89 cm in the first and second year, respectively. The number of leaves was on average 30.23 and 34.77 leaves in the first and second year, respectively.

A significant increase was observed in soil electric conductivity from the first cycle to the second cycle (Table 4). It can be supposed that soil salinity affected amaranth growth in the second cycle more than row and plant spacing did, thus leading to the non-significant results observed in the second cycle.

Table 5. *F*-test results and its level of significance for the growth characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement.

Sources of variation	DF	Plant height		Stem diameter		Number of leaves		Lodging index	
		1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Row spacing (R)	1	2.03^{ns}	0.33^{ns}	0.38^{ns}	1.095^{ns}	0.25^{ns}	2.41^{ns}	14.37^{*}	0.14^{ns}
Plant spacing (P)	2	0.02^{ns}	0.35^{ns}	8.22^{*}	2.06^{ns}	2.58^{ns}	1.48^{ns}	3.52^{*}	0.03^{ns}
R x P	2	0.06^{ns}	0.07^{ns}	3.45^{ns}	1.442^{ns}	1.17^{ns}	0.34^{ns}	0.29^{ns}	0.49^{ns}
Block	4	4.47^{ns}	2.42^{ns}	3.04^{*}	0.796^{ns}	3.56^{*}	0.58^{ns}	1.38^{ns}	1.62^{ns}

**Significant at 1% probability; * significant at 5% probability; ^{ns} non-significant.

During the first cycle, the plants with greater stem diameter were those cultivated at 40 and 30 cm plant spacing (22.72 and 22.39 mm, respectively), being statistically similar, whereas the 20 cm plant spacing resulted in lower stem diameter, being statistically different from the other two treatments (Table 6). This effect is probably related to intra-specific competition, since densely cultivated plots tend to be affected by self-shading, thus reducing photosynthesis and growth (FERREIRA et al., 2014).

Grain amaranth stem diameter is important because it is directly related to plant lodging, which is a relatively common phenomenon in grain amaranth and causes significant yield loss for the crop by impairing mechanical harvest (SILVA et al., 2019b).

Concerning the lodging index (Table 6), it was observed that it tends to increase by 20% as both the plant and the row spacings narrow; however, there was no interaction between these factors. Lodging is among the problems associated with excessively high grain amaranth populations (ESPITIA-RANGEL, 2018). However, grain amaranth lodging is also related to other factors such as nitrogen fertilization, strong winds, genotypes, and planting date (SILVA et al., 2019b). Besides the planting density, strong winds may have affected plant lodging in this study, since the time of the year in which the plants were in the field (September through December) has a history of intense winds in the study area (EMBRAPA, 2001).

Table 6. Growth components of grain amaranth *BRS Alegria* as a function of the planting arrangements.

Plant spacing (cm)	Stem diameter (mm) | 1st cycle
40	22.72 a
30	22.39 a
20	19.59 b
Row spacing (cm)	Lodging index | 1st cycle
40	11.47 b
30	14.53 a
Plant spacing (cm)	Lodging index | 1st cycle
40	11.74 b
30	12.90 ab
20	14.36 a

Means followed by the same letter in the columns do not differ by the Tukey test at 5% probability of error.

Biomass production

Row and plant spacing affected total aboveground fresh matter in both years, whereas total aboveground biomass (dry matter) was affected only during the first year. In the second cycle, total aboveground biomass (dry matter) was non -significant and weighed on average 10.36 t ha^{-1}(Table 7).

The total fresh matter yield of grain amaranth was favored by the narrower row and plant spacing in both cycles, with no interaction between these factors (Table 8). The use of narrow rows favored an increase in fresh matter yield of up to 25%, while the increase observed in the 20 cm plant spacing was approximately 45%.

Grain amaranth's high fresh matter production (above 100 t ha^{-1} for the narrowest row and plant spacings) in such a short time (about 55 days from transplantation to biomass collection), as well as its inherently high nutritional value, renders this pseudo cereal an interesting species to be explored as a source of forage in the Brazilian semi-arid region.

Similar effect was observed for the dry matter yield (Table 8), as the 30 x 20 cm arrangement resulted in the greatest dry matter yield (18.29 t ha^{-1}), a 30% increase compared to the 40 x 40 cm arrangement.

Table 7. *F*-test results and its level of significance for the biomass components of grain amaranth *BRS Alegria* as a function of the planting arrangements.

Source of variation	DF	Total aboveground fresh matter		Total aboveground biomass	
		1st cycle	2nd cycle	1st season	2nd season
Row spacing (R)	1	15.33**	23.89**	7.53*	0.31^{ns}
Plant spacing (P)	2	8.00*	45.54**	13.04**	2.06^{ns}
R x P	2	1.10^{ns}	1.65^{ns}	3.99*	0.05^{ns}
Block	4	5.93*	2.93^{ns}	4.05*	0.64^{ns}

** Significant at 1% probability; * significant at 5% probability; ^{ns} Non-significant.

Table 8. Biomass components of grain amaranth *BRS Alegria* as a function of the planting arrangement.

<table>
<tr><td rowspan="2">Row spacing (cm) [1]</td><td colspan="3">1st cycle</td><td colspan="3">2nd cycle</td></tr>
<tr><td colspan="3">Total aboveground fresh matter (t ha^{-1})</td><td colspan="3">Total aboveground fresh matter (t ha^{-1})</td></tr>
<tr><td>40</td><td colspan="3">70.22 b</td><td colspan="3">75.92 b</td></tr>
<tr><td>30</td><td colspan="3">89.34 a</td><td colspan="3">100.15 a</td></tr>
<tr><td>Plant spacing (cm) [1]</td><td colspan="3">Total aboveground fresh matter (t ha^{-1})</td><td colspan="3">Total aboveground fresh matter (t ha^{-1})</td></tr>
<tr><td>40</td><td colspan="3">58.82 c</td><td colspan="3">79.74 b</td></tr>
<tr><td>30</td><td colspan="3">76.37 b</td><td colspan="3">78.85 b</td></tr>
<tr><td>20</td><td colspan="3">104.16 a</td><td colspan="3">105.52 a</td></tr>
<tr><td rowspan="3">Row spacing (cm) [2]</td><td colspan="6">Total aboveground biomass (t dry matter ha^{-1}) | 1st cycle</td></tr>
<tr><td colspan="6">Plant spacing (cm)</td></tr>
<tr><td colspan="2">40</td><td colspan="2">30</td><td colspan="2">20</td></tr>
<tr><td>40</td><td colspan="2">12.73 aAB</td><td colspan="2">9.69 bB</td><td colspan="2">15.16 bA</td></tr>
<tr><td>30</td><td colspan="2">11.80 aB</td><td colspan="2">14.42 aB</td><td colspan="2">18.29 aA</td></tr>
</table>

[1]Means followed by the same letter in the columns do not differ by the Tukey test at 5% probability of error.
[2]Means followed by the same letter, lowercase in the columns and uppercase in the rows, do not differ by the Tukey test at 5% probability of error.

Gimplinger et al. (2007) reported that total aboveground biomass was not affected by crop density, whereas Henderson, Johnson and Schneiter (2000) reported that the greatest biomass yield was produced by the plants at the lowest population density. The greater biomass production achieved by the densely cultivated plots in this study is justifiable since plant growth was not significantly affected by the planting arrangements; thus, the greater plant populations achieved by the narrow row and plant spacings resulted in greater biomass yield per area.

Yield

Grain yield and harvest index were affected by the interaction between row and plant spacing in the first cycle, whereas these characteristics were affected by row and plant spacing separately in the second cycle (Table 9). Thousand-grain weight (TGW) was affected by the studied factors in the second crop cycle only, and in the first growing season the thousand-grain weight was on average 0.635 g.

Table 9. *F*-test results and its level of significance for the yield components of grain amaranth *BRS Alegria* as a function of the planting arrangement.

Source of variation	DF	Yield		Harvest index		Thousand-grain weight	
		1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Row spacing (R)	1	8.31*	8.95*	0.58^{ns}	10.51*	2.48^{ns}	17.04**
Plant spacing (P)	2	9.07*	0.02*	3.26^{ns}	9.06*	0.95^{ns}	4.37*
R x P	2	4.82*	0.44^{ns}	6.88*	0.68^{ns}	0.20^{ns}	5.19*
Block	4	0.26^{ns}	0.75^{ns}	5.50*	0.53^{ns}	0.61^{ns}	0.94^{ns}

**Significant at 1% probability; *significant at 5% probability; ns non-significant.

During the first growing season, the greatest grain yields were obtained by the 40 x 20, 30 x 40, and 30 x 20 cm spacings (1.56, 1.48 and 1.46 t ha^{-1}, respectively) (Table 10). The lowest grain yield was obtained by the 40 x 30 cm plant spacing (0.78 t ha^{-1}). In the second growing season, the greatest yields were also obtained by the plots cultivated under the narrowest row and plant spacing, 1.36 tha^{-1} for the 30 cm row spacing and 1.41 t ha^{-1} for the 20 cm plant spacing. The greater yields obtained by the narrow-cultivated plots could be related to a better ground coverage, which enabled a greater light interception and, therefore, better photosynthetic efficiency and allocation of resources for grain filling by the plants (CASINI; LA ROCA, 2015).

Casini and Biancofiore (2020) also reported greater yields (0.85 t ha^{-1}) when cultivating *A. cruentus* under narrow row spacing (18 cm), but these authors also point out that the selection of one mode of sowing over another will largely depend on the type of equipment available at the farm. In Brazil, according to Spehar, Teixeira and Lara (2003), in the Cerrado region this crop's yield reached up to 2.3 t ha^{-1} in succession to the soybean crop. The inherently limiting environmental conditions imposed by the semi-arid weather (i.e. high temperatures, saline water, poor soil quality, etc.) might be the reason behind the lower grain yields obtained in this study.

Table 10. Grain yield components of grain amaranth *BRS Alegria* as a function of the planting arrangements.

Row spacing (cm) [1]	Grain yield (t ha^{-1}) | 1st cycle		
	Plant spacing (cm)		
	40	30	20
40	1.17 aB	0.78 bC	1.56 aA
30	1.48 aA	1.33 aA	1.46 aA
Row spacing (cm) [2]	Grain yield (t ha^{-1}) | 2nd cycle		
40	0.94 b		
30	1.36 a		
Plant spacing (cm) [2]	Grain yield (t ha^{-1}) | 2nd cycle		
40	0.90 b		
30	1.14 ab		
20	1.41 a		
Row spacing (cm) [1]	Harvest index (HI) | 1st cycle		
	Plant spacing (cm)		
	40	30	20
40	9.40 bA	8.65 aA	10.83 aA
30	13.01 aA	9.63 aB	7.90 bB
Row spacing (cm) [2]	Harvest index | 2nd cycle		
40	9.07 b		
30	13.28 a		
Plant spacing (cm) [2]	Harvest index | 2nd cycle		
40	8.17 b		
30	10.50 b		
20	14.85 a		
Row spacing (cm) [1]	Thousand-grain weight (g) | 2nd cycle		
	Plant spacing (cm)		
	40	30	20
40	0.71 bA	0.70 bA	0.72 aA
30	0.82 aA	0.78 aAB	0.71 aB

[1]Means followed by the same letter in the columns do not differ by the Tukey test at 5% probability of error.
[2]Means followed by the same letter, lowercase in the columns and uppercase in the rows, do not differ by the Tukey test at 5% probability of error.

Concerning the harvest index, in the first growing season, the greatest harvest index was observed for the 30 x 40 cm spacing, and the lowest harvest index was observed for the 30 x 20 cm (Table 10). Zubillaga et al. (2020) also observed that the harvest index responded to rising plant density with decreasing figures. Considering that the harvest index is defined as the weight of grains divided by the total weight of aboveground biomass (stover plus grain), the results found here indicate that the aboveground biomass responded to the increased density to a greater extent than the grain yield did. On the other hand, during the second growing season the harvest index tended to increase with narrow spacing (Table 10). Since total aboveground biomass did not respond to spacing in the second growing season, the harvest index was able to increase by 46% with 30 cm row spacing (in comparison to 40 cm row spacing) and by 82% with 20 cm plant spacing (in comparison to 40 cm plant spacing).

Regarding the thousand-grain weight (TGW), in the second cycle, the greatest TGW was obtained with the 30 x 40 cm arrangement (Table 10). Overall, the 40 cm row spacing resulted in the lowest TGW values, which did not differ statistically among themselves. Grain weight is a function of the plant's ability to produce and store reserves (SCHMIDT, 2021), thus the lesser the impediments to plant's photosynthetic activity (i.e., self-shading) the more the plant can produce and store reserves. The TGW values obtained in this study are in accordance with the TGW values for *A. cruentus* found by Silva et al. (2019a) – approximately 0.7 g.

Grain quality

The lipid content was affected by the interaction between row and plant spacing during the first cycle and by the plant spacing alone during the second cycle (Table 11).

Table 11. *F*-test results and its level of significance for the quality characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement.

Source of variation	DF	Lipids content	
		1st cycle	2nd cycle
Row spacing (R)	1	46.23**	34.78**
Plant spacing (P)	2	22.97**	14.27**
R x P	2	17.03**	1.92ns
Block	4	1.303ns	0.91ns

**Significant at 1% probability; *significant at 5% probability; ns Non-significant.

Overall, it was observed that the lipid content in the grain tends to increase as plant spacing diminishes. In the first growing cycle, the greatest lipid content was obtained by plants cultivated in the 40 x 20 cm arrangement (9.60%), a 49% increase compared to the 40 x 40 cm arrangement (Table 12). There was no significant difference in lipids content among plant spacings when the row spacing was 30 cm and it ranged from 5.16 to 5.50%. In the second cycle, the greatest lipid content was obtained with the 20 cm plant spacing (3.87%). It could be speculated that the stress brought by intra -specific competition could have stimulated the plants in higher density plots to produce and store more reserves, thus the higher lipids content (SCHMIDT, 2021).

Table 12. Lipids content of grain amaranth *BRS Alegria* as a function of the planting arrangements.

Row spacing (cm)	Lipids content (%) | 1st cycle		
	Plant spacing (cm)		
	40	30	20
40	4.92 aC	7.82 aB	9.60 aA
30	5.16 aA	5.43 bA	5.50 bA
Plant spacing (cm)	Lipids content (%) | 2nd cycle		
40		1.84 c	
30		2.88 b	
20		3.87 a	

[1]Means followed by the same letter, lowercase in the columns and uppercase in the rows, do not differ by the Tukey test at 5% probability of error.
[2]Means followed by the same letter in the columns do not differ by the Tukey test at 5% probability of error.

CONCLUSION

The evaluated planting arrangements did not affect amaranth's plant height and number of leaves, but did affect stem diameter and plant lodging. In the Brazilian semi-arid region, under the study conditions, amaranth can yield up to 1.56 t ha^{-1} grain and 18.29 t ha^{-1} dry matter. The greatest lipid content was obtained at 40 x 20 cm spacing. It was observed that high plant densities results in greater biomass production and grain yield, therefore the 30 x 20 cm spacing could be recommended for amaranth cultivation for both grain and forage in the study area.

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