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VICTOR EMMANUEL DE VASCONCELOS GOMES

AGRONOMIC PERFORMANCE OF AMARANTH UNDER PLANTING ARRANGEMENTS AND THE EFFECT OF THE ENVIRONMENT ON ITS EMERGENCE AND EARLY GROWTH

FORTALEZA
2023

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Orientadora: Prof. Drª. Rosilene Oliveira Mesquita

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À minha mãe, **Ângela Marta de Vasconcelos.**

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RESUMO

O amaranto é um grão que tem ganhado destaque pois é bem adaptado as condições adversas de clima e solo, além de que detêm significativo potencial para ser melhor explorado tanto para alimentação humana como animal. Foram realizados dois experimentos: um experimento de campo objetivando avaliar como os arranjos de cultivo e densidades de plantio afetam o desempenho agronômico das plantas de amaranto; e um experimento sob condições de ambiente controlado (casa de vegetação) objetivando avaliar como a profundidade de semeadura e tipos de solo afetam a emergência e o crescimento inicial de duas cultivares de amaranto. Para atingir o primeiro objetivo foi conduzido um experimento em delineamento de blocos casualizados, em que foram testadas cinco densidades de plantio (62.500; 83.333; 111.111; 125.000 e 166.666 plantas ha^{-1}), em dois ciclos de cultivo (2019 e 2020), no município de Pentecoste-CE. Para atingir o segundo objetivo foi realizado um experimento avaliando a emergência e crescimento inicial de duas cultivares de amaranto (*A. cruentus* BRS Alegria e *A. caudatus* Inca) submetidos a três tipos de solo (franco, franco argiloso e argiloso) e cinco profundidades de semeadura (0; 5; 10; 15 e 20 mm) em delineamento de blocos casualizados em esquema fatorial 2x3x5. O experimento foi conduzidosi em dois períodos de avaliação, imediatamente subsequentes. As densidades de plantio tiveram pouco efeito sobre o crescimento das plantas afetando somente o diâmetro do caule e o tombamento de plantas, sendo que a densidade de 83.333 pl ha^{-1} favoreceu maior diâmetro de caule enquanto a densidade 62.500 pl ha^{-1} favoreceu menor índice de tombamento de plantas. A maior densidade resultou em maior produtividade de matéria fresca e seca, produtividade de grãos e índice de colheita. O peso de mil grãos foi maior na densidade 83.333 pl ha^{-1}. O arranjo espacial 30 x 20 cm com 166.666 pl ha^{-1} pode ser recomendado para o cultivo do amaranto na área de estudo. Com relação ao experimento em casa de vegetação, observou-se que o tipo de solo, a profundidade de semeadura e a cultivar tiveram efeito significativo na emergência e crescimento inicial do amaranto. *A. caudatus* apresentou maior altura de plântula, diâmetro do caule, número de folhas, comprimento da raiz e pesos fresco e seco. A emergência de plântulas foi afetada pela cultivar e foi 15% superior para a cultivar *A. cruentus*. A altura da planta foi maior quando as plantas foram semeadas a uma profundidade entre 5 e 20 mm. O comprimento radicular variou em função da interação entre tipos de solos e profundidade de semeadura sendo que o maior comprimente de raiz foi obtido quando se semeou o amaranto em solo franco ou argiloso a uma profundidade de 10 mm.

Palavras-chave: *Amaranthus cruentus* L.; *Amaranthus caudatus* L.; alimentos funcionais; morfofisiologia da planta; rendimento.

ABSTRACT

Amaranth is a grain that has gained prominence because it is well adapted to adverse climate and soil conditions, in addition to having significant potential to be better exploited for both human and animal consumption. Two experiments were carried out: a field experiment aimed at evaluating how cropping arrangements and planting densities affect the agronomic performance of amaranth plants; and an experiment under controlled environment conditions (greenhouse) aiming to evaluate how sowing depth and soil types affect emergence and initial growth of two amaranth cultivars. To achieve the first objective, an experiment was conducted in a randomized block design, in which five planting densities (62,500; 83,333; 111,111; 125,000 and 166,666 plants ha-1) were tested, in two cultivation cycles (2019 and 2020), in the municipality of Pentecoste-CE. To achieve the second objective, an experiment was carried out evaluating the emergence and initial growth of two amaranth cultivars (A. cruentus BRS Alegria and A. caudatus Inca) submitted to three types of soil (loam, clayey loam and clayey) and five soil depths. seeding (0; 5; 10; 15 and 20 mm) in a randomized block design in a 2x3x5 factorial scheme. The experiment was conducted in two immediately subsequent evaluation periods. Planting densities had little effect on plant growth, affecting only stem diameter and plant tipping over, with a density of 83,333 pl ha-1 favoring a greater stem diameter, while a density of 62,500 pl ha-1 favoring a smaller plant tipping index. Higher density resulted in higher fresh and dry matter yield, grain yield and harvest index. The weight of a thousand grains was higher in the density 83,333 pl ha-1. The 30 x 20 cm spatial arrangement with 166,666 pl ha-1 can be recommended for the cultivation of amaranth in the study area. Regarding the greenhouse experiment, it was observed that the soil type, sowing depth and cultivar had a significant effect on emergence and initial growth of amaranth. A. caudatus showed the highest seedling height, stem diameter, number of leaves, root length, and fresh and dry weights. Seedling emergence was affected by the cultivar and was 15% higher for the A. cruentus cultivar. Plant height was greatest when plants were sown at a depth between 5 and 20 mm. Root length varied as a function of the interaction between soil types and sowing depth, with the longest root length being obtained when amaranth was sown in loam or clayey soil at a depth of 10 mm.

Keywords: *Amaranthus cruentus* L.; *Amaranthus caudatus* L.; functional foods; plant morphophisiology; yield.

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SUMMARY

1 GENERAL INTRODUCTION

The potential effects of climate change on the global agricultural production, such as yield loss, desertification, deforestation, erosion, loss of water quality and hydric resources scarcity, have been largely reported as the future challenges for guaranteeing global food security, mainly in areas in which agriculture is already vulnerable to climate, such as the arid and semi-arid regions (D'ODORICO et al. 2013, DELGADO et al. 2011). The combination of global population growth and the aforementioned factors along with the increase in electricity costs and the resulting increase in the cost of agricultural inputs will add up to the challenges of guaranteeing food security in a climate change scenario (FUJIMORI et al., 2019).

To further aggravate this situation, current agricultural production relies on only nine crops to provide for 75% of the global demand for plant-based foods, in which three grains (wheat, rice and corn) account for more than 50% of the total (JACOBSEN et al. 2015; Among the recommended strategies to adapt to these changes is the adoption of more diversified agricultural systems that include crops that are heat and/or drought tolerant (BRASIL, 2016a; BRASIL, 2016b; EMBRAPA, 2017; LASCO et al., 2014). It is therefore important to have a deeper understanding about alternative and underutilized crop species with the potential to feed a constantly growing global population in the coming decades. Among the underused species with such potential, it is included the grain amaranth (*Amaranthus* spp. L.), the quinoa (*Chenopodium quinoa* Wild.), the buckwheat (*Fagopyrum esculentum*) among others (CHENG, 2018).Grain amaranth is well adapted to marginal lands and holds a significant potential for further development and adaptation, due to its high genetic diversity and phenotypic plasticity (ECKER et al., 2010; EMIRE; AREGA, 2012; RASTOGI; SHUKLA, 2013). The combination of these characteristics with its inherent tolerance to high temperatures, drought, poor soils, and lack of phytosanitary problems render grain amaranth an interesting crop to be cultivated under adverse conditions (FUENTES REYES et al., 2018). Due to its relatively high revenue price and the rising popularity in the Western world, grain amaranth may constitute a stable source of income for the subsistence of farmers (EMIRE; AREGA, 2012).

From a nutritional standpoint, the main characteristics of this species are the high protein content (15 - 18%), as well as the lysine and calcium contents, 5.2 and 0.37 g $100g^{-1}$ of dry matter, respectively (PETR et al., 2003). The lysine content is higher in the amaranth grain than in other plant-based products (i.e., wheat, beans, and soybeans) and certain animal sources (meat, milk, and eggs), thus ensuring a high marketability potential. This species stands out for the absence of gluten in its composition, thus being recommended for celiac diets (BALLABIO et al., 2011). Grain amaranth can also be explored outside of the food sector. The cosmetic and pharmaceutical industries could benefit from the high squalene content (4-5%) in the oil produced from the amaranth seeds (HE et al., 2002; BERGANZA et al., 2003).

Currently, Brazil has a grain amaranth cultivar developed and recommended for countrywide cultivation, the BRS Alegria cultivar. *Amaranthus cruentus* L. BRS Alegria is originated from the *A. cruentus* AM 5189 lineages, coming from the United States. From 1988 onwards, after two years of evaluations, mass selection and standardization in relation the agronomic traits were carried out in the AM 5189 lineage (SPEHAR et al., 2003).

It is therefore important to evaluate new materials that present good adaptation potential to adverse conditions, in a climate change scenario and increase in food demand, as well as to define the plant management parameters for the best performance of such materials. Regarding the other crop management attributes, when considering the planting characteristics, Henderson et al. (2000) report that in order to maximize grain yield, the adoption of cultivation practices that include the adequate planting date, sowing depth, fertilization and planting density for each cultivar, along with other inputs, is essential.

Henderson et al. (2000) also point out that in dry regions the optimal planting density for the K283 (*A. cruentus*), K343 (*A. hypocondriacus* x *A. hybridus*), K432 (*A. hypocondriacus* x *A. hybridus*) and MT-3 (*A. cruentus*) genotypes is 20,000 to 30,000 plants ha^{-1}. Guillen-Portal et al. (1999) suggest 50 plants m^{-2} for the ‘Plainsman’ hybrid cultivar as the optimum for arid and semi-arid regions. Franke (1997), however, reported that in arid regions, highly dense stands may cause a reduction in grain yield and result in thinner and longer stems, due to the competition for water among the plants. In Nigeria, for *A. cruentus*, the recommended plant population for higher grain yield was 60.000 pl ha^{-1} (OLOFINTOYE et al., 2015).

For the Brazilian Midwest, Guimarães (2013) reports that the recommended density for cultivars of *Amaranthus hypochondriacus* e *Amaranthus cruentus* L. is 32,000 plants ha^{-1}, ideal to achieve high yields and for good crop management. For the production of vegetable amaranth densities of up to 100,000 plants ha^{-1} are used (NATIONAL RESEARCH COUNCIL, 1984). However, currently there is no reference regarding the planting date and density or other crop management practices for this crop for the Brazilian Northeast. Therefore, the conduction of research that aims to establish a set of recommended management practices for the obtention of its best performance under different environmental conditions is relevant (TEIXEIRA et al., 2003).

Because of the scarcity of information about the effects of the planting arrangements for the cultivation of grain amaranth in the Brazilian semi-arid as well as the scarcity of studies that aim to investigate how grain amaranth cultivars respond to environmental factors in terms of emergence and initial growth, three experiments were carried out: one field experiment, aiming to evaluate how the planting arrangements (row and plant spacing) affect the agronomic performance of grain amaranth plants; and two experiments under controlled environment conditions (greenhouse and growth chambers) aiming to evaluate how sowing depth and soil types affect emergence and early growth of two grain amaranth cultivars.

2 HYPOTHESIS DEVELOPMENT AND OBJECTIVES

This study aimed to answer two questions: 1) does the planting arrangement affect grain amaranth agronomic performance in the Brazilian semi-arid?; 2) How do the environmental factors such as soil type and sowing depth affect emergence and early growth of grain amaranth? Based on these questions we proposed the hypothesis that grain amaranth's agronomic performance is dependent upon the planting arrangement. We also hypothesized that seedling emergence and early growth of grain amaranth is dependent upon several factors such as: soil type, sowing depth, cultivars and their interactions.

3 EXPERIMENTAL STRATEGY

To test the hypotheses the study was carried out in three stages, two of each were sequential and dependent on each other, and the results allowed producing three scientific papers, that can be found in Chapters I and II.

In the first stage, described in detail on Chapter I, *Amaranthus cruentus* L. BRS Alegria was grown under five different planting densities (62,500, 83,333, 111,111, 125,000 and 166,666 plants ha^{-1}), in two years, in the municipality of Pentecoste-CE, in the Brazilian semi-arid, aiming to find out what is the planting density that allows for the best agronomic performance of grain amaranth, and to understand how it affects growth and yield. In this stage, the hypothesis that the planting density affects the agronomic performance of grain amaranth was confirmed and although the densities that were evaluated produced little response in terms of plant growth, it significantly affected grain and biomass yield as well as grain quality parameters of *A. cruentus*.

Stages two and three aimed to evaluate how the environmental factors affect the emergence and early growth of two grain amaranth cultivars. The two experiments demanded for different experimental conditions: the first one was carried out under greenhouse conditions and the second one was carried out in growth chambers. These studies were sequential and dependent on each other.

During stage two (Chapter II), which aimed to evaluate how three soil types (clay, clay-loam and loam) and five sowing depths (0, 5, 10, 15 and 20 mm) affect the emergence of two grain amaranth cultivars (*A. cruentus* BRS Alegria and *A. caudatus* Inca) in two runs under greenhouse conditions. In this study we observed that the soil type, sowing depth, and cultivar had a significant effect on germination and early growth of grain amaranth, thus confirming the hypothesis. These results are discussed in detail in Chapter II.

4 LITERATURE REVIEW

4.1 The Amaranth genus (*Amaranthus* sp.)

Amaranth is the collective name of approximately 60 members of the Amaranthus genus, belonging to the Amaranthaceae family, which comprises many a cultivated species used mainly as grain and leafy vegetables (MLAKAR et al., 2010).

Native to Central and South Americas, amaranth was probably domesticated for the first time as a grain plant around 8,000 years ago by the Aztecs. Like quinoa, amaranth was once a sacred grain for the pre-Columbian societies, which vanished into obscurity when the Spaniards arrived in the Americas five centuries ago (KAUFFMAN; WEBER, 1990; STALLKNECHT; SCHULZ-SCHAEFFER, 1993; BRENNER, 2000; HABER et al., 2017). This grain reappeared in the 1970's mainly due to its high nutritional value; with high lysine contents, an amino acid that is absent in most grains (SUNIL et al., 2014). Lysine is a highly important amino acid for the organism, for it has antiviral action and it also facilitates calcium absorption. However, this amino acid is not synthetized by the human body, which makes it necessary to be ingested through the food (SUNIL, 2014).

Three amaranth species have been cultivated almost exclusively for the obtention of grains since ancient times: *A. caudatus*, *A. cruentus* and *A. hypocondriacus* (STETTER et al., 2015). These are hot climate C4 annual species, and they show good drought tolerance and can easily adapt to new environments with limiting and even extreme conditions (DELANO-FRIER et al., 2011). Along with two weed species: *A. hybridus* and *A. quitensis*, they form the hybridus species complex, however, the limits among these five species are vague (KIETLISNKI et al., 2014; ADHKARY; PRATT, 2015). A phylogenetic analysis carried out by Stetter and Schmid (2017) points out that *A. hybridus* probably is the ancestor of the three cultivated species, while *A. quitensis* maybe an intermediary between *A. hybridus* and *A. caudatus*.

Amaranth is presented in different forms. Some species have leaves, stems and flowers tinged in orange, red, purple or golden while the seeds vary between black or white (National Research Council [NRC], 1984). Many species of the Amaranthus genus are grown as ornamental plants worldwide. Its growth habit varies between prostrated and erect and between branched or unbranched (NRC, 1984; KOCHHAR, 1986).

Concerning its cultivation and the crop management, it has been reported that its water requirement is 42-47% that of wheat, 51-62% that of corn and 79% that of cotton (WEBER, 1990). There is not a consensus as for the rates of application of mineral fertilizers, but adaptations from the recommendations for corn, sorghum and other grain crops have been used in different parts of the world, however, in most researches, amaranth has responded to increased mineral fertilization rates with a significant increase in yield (TYRUS; LYKHOCHVOR, 2022). As for the soil, ideally, the soil should be well-drained, deep, fertile, rich in organic matter and with a pH between 5.5 and 7. However, these plants are quite tolerant in terms of soil type, tolerating even slightly saline soils or soils subject to flooding for short periods (ACHIGAN-DAKO et al. 2014). In terms of light requirement, amaranth will be most productive in full sun (i.e., at least six hours of direct sunlight) (UFOEGBUNE; ERUOLA, 2016).

4.1.1 Amaranth and its consumption as grains

The amaranth presents panicle type inflorescences, being frequently classified as a pseudo-cereal. This plant’s inflorescences are similar to that of sorghum and its seeds are diminutive and little bigger than the mustard seed (0.9 to 1.7 mm diameter). The seeds occur in great quantities, sometimes more than 50,000 per plant and its color can be either cream, golden, purple, or black (ALVAREZ-JUBETE et al., 2010). The three main species considered for grain production are: *Amaranthus hypochondriacus*, *A. cruentus* and *A. caudatus*, which are distinguished by their morphological characteristics of inflorescences and florets (MLAKAR et al., 2010).

It is believed that the *A. cruentus* L. species is the most adaptable of all the cultivated species, being able to flower under different photoperiodic conditions (FACCIOLA, 1990). It is also cultivated as a vegetable or an ornamental plant, while *A. hypocondriacus* holds excellent grain quality and presents the highest potential to be used as a culinary ingredient (SILVA-SANCHEZ et al., 2008).

Regarding the utilization of the grain, the native people from Mexico, Peru and Nepal already used the grains in their diets a long time ago, way before any nutritional analysis was conducted. In these regions, the ingestion of amaranth is commonly recommended for people in the process of recovery from illness, due to its easy digestion (TIWARI; SONI; LANDHE, 2012).

For human consumption, the amaranth grains have been used in many ways, in which the flour production from the milled grains is the most common. The flour from the milled grains can be used to produce loaves, pancakes, cereal bars, cakes, and other baked goods (GALLEGOS-INFANTE, 2010). The grain can also be popped like popcorn or processed as flakes, like oatmeal. It is important to mention, however, that the making of the flour must follow a series of procedures aiming to inactivate or to reduce the concentration of anti-nutritional factors present in the grain (BIANCHINI; BELEIA, 2010).

In Mexico and Peru, the grains are popped and mixed with sugar molasses to obtain a candy named alegria (México) or turrones (Peru), and this is the most common commercial use for amaranth. The atole, traditional Mexican alcoholic beverage is made from ground and toasted amaranth seeds (MAZZINI, 2019). In India, *A. hypocondriacus* is known as rajgeera (King grains) and is frequently toasted to be obtain the laddoos which is very similar to the Mexican alegria. In Nepal, the amaranth seeds are consumed as source of energy or milled into flower to produce chapatis (SINGHAL; KULKARNI, 1988). Even though grain amaranth has characteristics that favor its usage by the food industry, it has not yet been effectively commercialized worldwide, in comparison with rice, corn and wheat.

Grain amaranth has the potential to be explored beyond the food industry. The lipophilic fraction of grain amaranth contains valuable edible oil with a high content of unsaturated fatty acids, squalene, and a range of minor compounds such as tocopherols, phytosterols, waxes, terpene alcohols and hydrocarbons. Health benefits of bioactive components present in the unsaponifiable lipid fraction of amaranth, particularly those exhibited by squalene and tocopherols, have been reported in many studies (LIPPI; TARGHER; FRANCHINI, 2010). Studies have shown that squalene can be included among the foods that are efficient in reducing cholesterol in the blood (SHIN et al., 2004; GONOR et al., 2006). The amaranth oil, contained in the seeds, comprehends in average 6.0% of the seed weight (KRAUJALIS; VESUKTONIS, 2013).

4.1.2 Utilization of leaves and inflorescences

The species from the *Amaranthus* genus more commonly used as vegetables have low size and broad leaves with small inflorescences (VENSKUTONIS; KRAUJALIS, 2013). However, some species can be used for the production both of grains and leaves.

In terms of biomass production, the *A. cruentus* L. can reach up to 2 meters tall in three months e has high biomass yield capacity and can be used as forage with high nutritional quality (SPEHAR et al., 2003; AYNEHBAND, 2008). Maybe because of this peculiarity amaranth has reached dry matter yields of 4.5 t ha^{-1} in a few weeks (TEUTÔNICO; KNORR, 1985).

According to Das (2016), amaranth usage in the different cultures around the world is multiple. In the Cuzco region, the flowers of the wild amaranth (airampo) are used to treat toothache and fever. The heated-up inflorescences have also been used to color corn and the beverage known as chicha. During the carnival festivities, the female dancers paint their faces with the red inflorescences, as some sort of rouge and dance carrying amaranth bags on their backs as if they were babies. In Ecuador, the leaves are heated-up and added to rum to purify the blood. It has also been used by women when they need help to regulate their menstrual cycle. In Asia and Western India, it has been used in soups.

In contrast to the grains, the vegetative parts of the amaranth plant have received less attention when it comes to research. However, it is known that the green biomass of some amaranth species has the potential to be used as a high-quality animal feed. Characteristics such as rapid growth, efficient water usage and high protein content throughout the plant render amaranth an adequate to crop to be used as animal feed. It is reported that the amaranth seed has a very favorable chemical composition (ŽAJOVÁ et al., 2001; POSPIŠIL et al., 2008). Research, however, have shown that a high nutritional value can also be found in the amaranth biomass (STORDAHL et al., 1999; PISARIKOVA et al., 2007). The amaranth genotypes with high dry matter yield and higher leaves percentage are the most adequate for forage production (KANENSI et al., 2011). Table 1 presents the average nutritional composition of 100 g of dried amaranth leaves.

Table 1 - Average nutritional composition in 100 g amaranth leaves dry matter.

Component	**Unit**	**Quantity**
Moisture	g	86.9
Protein	g	3.5
Lipids	g	0.5
Carbohydrates	g	6.5
Potassium	mg	411
Vitamin A	u.i.	6.1
Ascorbic acid (vitamin C)	mg	80
Tiamin	mg	0.08
Fiber	g	1.3
Calories	kcal	36
Phosphorus	mg	67
Iron	mg	3.9
Riboflavin	mg	0.16
Niacin	mg	1.4
Ash	g	2.6
Calcium	mg	267

Source: J. N. Cole, Amaranth: from the Past, for the Future, Rodale Press, Emmaus, PA (1979).

The forage quality also depends on the development stage of amaranth. Havilah (2011) has observed a decrease in amaranth’s fresh biomass quality from bud formation to flowering. Stordahl et al. (1999) reported that the highest protein content during the vegetative stage (230 g kg^{-1} dry matter) significantly decreased in later stages (130 g kg^{-1} dry matter), while the neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents in the stems increased.

4.1.3 *Amaranthus cruentus* **L.** ***BRS Alegria cultivar***

The *A. cruentus* BRS Alegria cultivar was developed by the Embrapa (Brazilian Agricultural Research Company) Cerrado in the early 2000's and is the first cultivar to be recommended for cultivation in Brazil.

Concerning this cultivar's morphology, the hypocotyl has a pinkish color, the leaves are wide, green and elongated, with nerves that also have a pinkish color on its abaxial face. The stem also has a pinkish color. The inflorescence is terminal, compact and has a pinkish color which persists even after the plant reaches its physiological maturation. The grain is contained within dehiscent fruits of the pyxidium kind, and they are round and beige in color. The plant's drying out after maturation is slow. When the cultivation occurs during the off-season the plants mature during the dry season, which allows for the plant to dry out and the grain to be harvested (SPEHAR et al., 2003).

The adult plants are in average 180 cm tall and the inflorescences about 48 cm. The grain reaches physiological maturity at 90 days after sowing and is ready for storage at 12% moisture. It has an average weight of 0.68g per 1.000 grains and protein content of 15%. This cultivar is also resistant to lodging and showed an average grain yield of 2.3 t ha^{-1} and 5.5 t ha^{-1} of total dry biomass in a 90-day cycle (FERREIRA et al., 2014). For comparison, between 2010 and 2019, the average yield of Brazilian wheat was 2,523 kg ha^{-1}, while in the Southern region it was 2.492 kg ha^{-1}, in the Southeast 2,830 kg ha^{-1} and in the Mid-West 3,186 kg ha^{-1}.

4.1.4 *Amaranthus caudatus L. Inca variety*

Like other species belonging to the Amarathus genus, *A. caudatus* has several characteristics that make it an attractive crop. In fact, *A. caudatus* readily adapts to new and challenging environments, including some environments unsuitable for most grain crops (MARTINEZ-LOPEZ, 2020).

Concerning this species morphology, the central stem can reach 2 to 2.5 m in height when the plant reaches maturity, although some varieties are smaller. The cylindrical branches can start as low as the base of the plant depending on the variety. The main root is short and the secondary roots run downwards into the soil. The flowers sprout from the main stem, in some cases the inflorescences measure 90 cm (COSTEA et al., 2006).

The plant easily adapts to many different environments, has an efficient type of photosynthesis (C4), grows quickly and does not require much maintenance. It occurs at altitudes between 1,400 and 2,400 m.

The *A. caudatus* Inca variety has been reported to achieve up to 1.5 t ha^{-1} grain yield in a 63-day crop cycle (SILVA et al., 2019) and was selected for this study because of its morphological characteristics, that differ in relation to *A. cruentus*, i.e. growth habit, inflorescence shape, leaf color, etc.

4.2 Agronomic performance of grain amaranth

Amaranth is a plant species with multiple vocations. In regard to its grain production, it is reported that there is a broad range of variation according to the site of cultivation and the genotype. The yield levels are usually between 500 and 2,000 kg ha^{-1}, however, good agronomic management practices could elevate this value up to 3,000 kg ha^{-1} (WILLIAMS; BRENNER, 1995). Myers (1996) has reported a 1,000 kg ha^{-1} yield in experimental fields in different regions of the United States, some of which obtained yields higher than 3,000 kg ha^{-1}, however such a yield was only replicated in some of the experimental plots.

In the German Southwest, the manual harvest of *A. cruentus* L. and of lineages of *Amaranthus hypocondriacus* x *A. hybridus* resulted in yield ranging from 2,100 – 3,300 kg ha^{-1} (AUFHAMMER; KÜBLER, 1998; KAUL et al., 2000).

In Slovakia, average yields between 2,100 and 2,700 kg ha^{-1} were obtained from *A. hypocondriacus* and *A.cruentus* (JAMRISKA, 1996; 2002).

In Croatia, *A. hypocondriacus* and *A. cruentus* lineages yielded between 1,300 and 2,600 kg ha^{-1} (POSPISIL et al., 2006).

Under Mediterranean climate conditions, in Southern Italy, the yield of 22 amaranth accesses ranged from 1,200 to 6,700 kg ha^{-1}, the latter coming from *A. caudatus* (ALBA et al., 1997).

4.2.1 Agronomic performance of grain amaranth as a function of the planting arrangement

The comprehension about a crop's response to spacing and planting density is crucial for yield improvement because both factors play an important role in the resulting yield. Variations in these characteristics of plant management might exert either positive or negative effects on grain yield and other agronomical parameters (FERREIRA et al., 2014).

It is well documented that the morphological traits of grain amaranth will respond to planting density (WEBER et al., 1989; GUILLEN-PORTAL et al., 1999; HENDERSON et al., 2000; IGBOKWE; HOLLINS, 2000). The population pressure may limit the plant growth (WEBER et al., 1989; HENDERSON et al., 2000). Even then, as with any other crop, the crop's response in terms of plant height is also subject to environmental conditions such as water, light and nutrients availability (GUILLEN-PORTAL et al., 1999). Increases in plant population may result in smaller inflorescences and stem diameters (FITTERER et al., 1996; GUILLEN-PORTAL et al., 1999) while a low planting density may result in bigger inflorescences (O'BRIEN; PRINCE, 2008). Thus, according to these authors, it seems like there is an optimum where the yield is not affected by planting density. The same authors concluded that a higher plant density might facilitate the mechanical harvesting of grain amaranth due to less branching and smaller stem diameter.

Regarding the grain yield, however, investigations that consider the effects of plant density have been inconclusive. Many studies have shown only a moderate response (GUILLEN-

PORTAL et al., 1999; HENDERSON et al., 2000) or even no response at all (MYERS, 1996). Nevertheless, some authors reported an increase in grain yield with the increase in plant population (PEIRETTI; GESUMARIA, 1998; APAZA-GUTIERREZ et al.,., 2002; KÜBLER et al., 2002; MALLIGAWAD; PATIL, 2001).

Henderson et al. (2000) reported that grain amaranths response to planting density is influenced by the environmental conditions, just like what happens with other crops (SHRIEF et al., 1990). In the Brazilian Cerrado, Ferreira et al. (2014) have found that for the inflorescence and grain dry matter, the higher planting densities, in general, have shown similar results and had the best response. On the other hand, the plant height, the length and width of the inflorescences and the stem diameter showed lower values under the higher densities.

Currently, no specific standards have been established for the optimum amaranth plant density, nor have data been compared from different geographic regions (ALEMAYEHU et al., 2015).

Studies conducted in Peru on *A. caudatus* indicated that optimum grain yields can be obtained at plant densities of about 450,000 plants ha^{-1} (APAZA-GUTIERREZ et al., 2002). In Argentina, Zubillaga et al. (2020) reported that the optimum plant density for *A. cruentus* cv. Mexicano was 116,000 plants ha^{-1} with a row spacing of 0.70 m. According to Ansariardali; Aghaalihkani (2013) a planting density of 140,000 plants ha^{-1} of *A. hypocondricaus* showed superiority over the other treatments and represented better agronomic characteristics in studies conducted in Iran.

In Brazil, it has been reported that in the Brazilian Midwest the population density with the highest productive potential of *A. cruentus* L. *BRS Alegria* cultivar is between 228,000 and 242,000 pl ha^{-1} (PITTELKOW et al., 2019). Also for the Brazilian Midwest, Guimarães (2013) reports that the recommended density for cultivars of *Amaranthus hypochondriacus* and *Amaranthus cruentus* L. is 320,000 plants ha^{-1}, ideal both for good yield and good crop management. In synthesis, the recommendations concerning the optimal planting density and spacing have diverged significantly in the scientific literature and the amount of data that has been published concerning grain amaranth’s response to planting arrangements and densities in the Brazilian semi-arid is lacking.

4.3 Environmental factors on the emergence and early growth of grain amaranth

When studying a new crop or cultivar, the evaluation of the germination and initial growth of plants subjected to different conditions is the first step towards understanding the effects of the environment on plant morphology and production (MONTEIRO et al., 2016). Aufhammer et al. (1994), Kauffman (1992) and Webb et al. (1987) reported that edaphoclimatic factors such as soil type, sowing depth and light regime directly affect germination and initial growth of grain amaranth.

Seeding depth is crucial for the success of this crop. Under shallow sowing conditions, amaranth germination might be inhibited by light, especially under low air temperature conditions (GUTTERMAN et al., 1992; RODRIGUES et al., 2016). However, because of the low reserves content in its seeds, sowing depth must not be deeper than 20 mm (SANTOS et al., 2019).

Soil type plays an important role in amaranth germination and this role is mainly related with the nature of the soil surface (AUFHAMMER, 1994). Surface soil crusting strongly reduces amaranth emergence (KAUFFMAN; HASS, 1983) and this is a phenomenon of relatively common occurrence in Ohio. Soil crusting most often occurs when rain separates the soil into very small aggregates and individual particles that cement into hard layers at the soil surface when drying occurs rapidly (LE BISSONAIS, 1996). Studies aiming to investigate how the growth characteristics of different plant species respond to local soils are important to facilitate the development of management practices for greater yield with good quality (HOSSAIN; ISHIMINE, 2005).

Regarding the genotype choice, given that grain amaranth has a higher demand for heat than moisture, cultivars with a fast development and a growth cycle of no more than 100 days must be preferred when being cultivated under temperate conditions (DMITRIEVA; IVANOV, 2020).

5 CHAPTER I[1] - AGRONOMIC PERFORMANCE OF GRAIN AMARANTH IN THE SEMI-ARID AS A FUNCTION OF THE PLANTING ARRANGEMENT

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. The aim of this work was to evaluate how planting arrangements affect the agronomic performance of grain amaranth BRS Alegria cultivar grown in semi-arid conditions. Two experiments were 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); during the 2019/20 and 2020/21 crop years, in the Pentecoste-CE municipality. The evaluated characteristics were: plant height, stem diameter, number of leaves, fresh matter yield, aboveground biomass yield (dry weight), grain yield, one-thousand grains weight, lipid content in the grains, harvest and lodging indexes. The evaluated planting arrangements had little effect on plant growth, affecting solely the stem diameter in which the 40 cm plant spacing was the one that favored greater stem diameter. Narrow spacing resulted in a higher lodging index but also resulted in a higher fresh matter yield, aboveground biomass, grain yield, harvest index and lipid content in the grain. The one-thousand grain weight was favored by the 30 x 40 cm spacing. The 30 x 40 cm arrangement can be recommended for the cultivation of grain amaranth in the study area.

Key words: *Amaranthus cruentus* L; adaptability; functional foods; plant morphology; yield.

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DESEMPENHO AGRONÔMICO DO AMARANTO GRANÍFERO NO SEMIÁRIDO EM FUNÇÃO DO ARRANJO ESPACIAL

RESUMO

Os potenciais efeitos das mudanças climáticas sobre a produtividade agrícola demandam por uma melhor compreensão acerca dos sistemas produtivos que incluam culturas agrícolas subutilizadas com elevada capacidade adaptativa aos estresses hídrico e térmico, como o amaranto. O objetivo com este trabalho foi avaliar como arranjos espaciais afetam o desempenho agronômico do amaranto BRS Alegria cultivado em condições semiáridas. Foram realizados dois experimentos com delineamento em 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); durante os anos 2019 e 2020/21, no município de Pentecoste – CE. As características avaliadas foram: altura da planta, diâmetro do caule, número de folhas, produtividade de matéria fresca, produtividade de biomassa sobre o solo (peso seco), produtividade de grãos, peso de mil grãos, teor de lipídios nos grãos e os índices de colheita e de acamamento. Os arranjos espaciais tiveram pouco efeito sobre o crescimento das plantas afetando somente o diâmetro do caule e o espaçamento de 40 cm entre plantas foi aquele que favoreceu maior diâmetro do caule. O espaçamento mais estreito resultou em maior índice de acamamento, porém também resultou em maior produtividade de matéria fresca, biomassa sobre o solo, produtividade de grãos, índice de colheita e teor de lipídios nos grãos. 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.

5.1 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 widely reported as the major threats for guaranteeing global food security in the future, mainly in areas in which agriculture is already climate sensitive, such as the arid and semi-arid regions (MAYES et al., 2012). The combination of the afore mentioned factors with 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, 2016a; BRASIL, 2016b; EMBRAPA, 2017; LASCO; DELFINO; ESPALDON, 2014). According to Spehar (2003) 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.

In this scenario, 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 (EMIRE; AREGA, 2012; RASTOGI; SHUKLA, 2013). The combination of these characteristic with its inherent tolerance to high temperatures, drought, nutrient poor soils and the lack of phytosanitary issues render grain amaranth a highly interesting crop to be cultivated under adverse conditions (FUENTES-REYES; CHÁVEZ-SERVÍN; GONZÁLEZ-CORIA, 2018). Due to its relatively high sale price and ever-growing popularity in the Western world, grain amaranth might become a steady source of income for farmers (EMIRE; AREGA, 2012).

Besides the adaptive characteristics of grain amaranth, this pseudo-cereal 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).

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 in highest planting densities, while the plant height, inflorescence length and width and the stem diameter tend to be negatively affected by the highest density. Pittelkow et al. (2019) reported that, for the Brazilian Midwest, the population density with the highest productive 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 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 is non-existing.

Given the lack of information regarding the effects of the planting density of grain amaranth in the Brazilian semi-arid, two field experiments were carried out during two cycles, aiming to evaluate how the interaction between the aforementioned factors affects the agronomic performance of *A. cruentus* BRS Alegria cultivar.

5.2 Materials and methods

5.2.1 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, 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 from the area is classified as Solodic Eutrophic Haplic Planosol (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 2.

Table 2 - Environmental data from the study area during the experimental period. Pentecoste – CE, 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.

Rh% = Air relative humidity

5.2.2 Treatments and experimental design

The experiment was carried out in a complete randomized block design with five treatments and five replications, making up for 25 plots (Table 3). 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}.

Table 3 - Evaluated row and plant spacings and their resulting plant densities. Pentecoste – CE, 2019 - 2020.

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

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

5.2.3 Experimental set up

Soil tillage consisted of weeding and incorporating 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; 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 4 and Table 5. Concerning the water analysis, the characteristic that stands out the most is the high electric conductivity during both cycles, which renders the water to be classified as C_3S_1 (inadequate for usage in poorly drained soils and must be used for salt tolerant crops only) according to the US Salinity Lab Classification System (RICHARDS, 1954).

Table 4 - Water analysis results. Pentecoste – CE. 2019 - 2020.

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	6.9	1,190

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

The soil in the experimental area presents low levels of both macro and micronutrients (Table 5). The pH level of the soil is slightly above the adequate range recommended for agricultural purposes, being considered as slightly alkaline. A significant increase in the soil's electric conductivity was observed in the second cycle. This is probably due to the accumulation of salts from irrigation water.

Table 5 - Soil chemical analysis results. Pentecoste – CE, 2019 - 2020.

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 extractor

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 diminutive (roughly 1 – 1.5 mm diameter) and no machinery was available, achieving the aimed arrangements by sowing manually would be very difficult, therefore, transplanting was preferred.

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

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 potash (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 (N) (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). For the spraying of the fertilizer a 20 L back sprayer was used, and recommendations for cereal production were followed (200 g 100 L^{-1} of water) and the spraying took place during the cooler hours of the day (early morning or evening). The change in the fertilizer formulation aims to stimulate flowering and to reduce vegetative growth by increasing the P contents and decreasing N and K contents (OLIVERA 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 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 et al., 2003). Plant collection for biomass analysis was performed 15 days prior to grain harvest.

5.2.4 Evaluated characteristics

Growth and yield

For the growth evaluation, three plants per plot were measured at the end of the crop's cycle (60 days after transplanting) 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 until 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 grain was weighed to determine the grain yield (t ha^{-1}) and the thousand grains weight (g). The harvest index (%) was calculated using the formula:

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

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. (2019):

$$PLI = \frac{h\ x\ IW}{d\ x\ SW}$$

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).

Grain quality

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

5.2.5 Statistical analysis

The obtained data were submitted to normality and homogeneity tests. Afterwards, the analysis of variance was performed separately for each crop cycle (2019 and 2020) and whenever significant ($p<0.05$) the data were then subject to regression analysis, using SISVAR® statistical software (FERREIRA, 2019). Graphs were plotted using Microsoft Excel®.

5.3 Results and discussion

5.3.1 Growth

Among the evaluated growth characteristics only the stem diameter and the lodging index were significantly affected by the planting arrangements ($p<0.05$), both in the first year (Table 6). In the second cycle stem diameter was in average 18.11 mm and the lodging index was in average 18.84. Plant height was in average 159.64 and 148.89 cm in the first and second year, respectively. The number of leaves was in average 30.23 and 34.77 leaves in the first and second year, respectively.

Table 6 **-** *F*-test results and its level of significance for the growth characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement. Pentecoste, CE – 2019 - 2021.

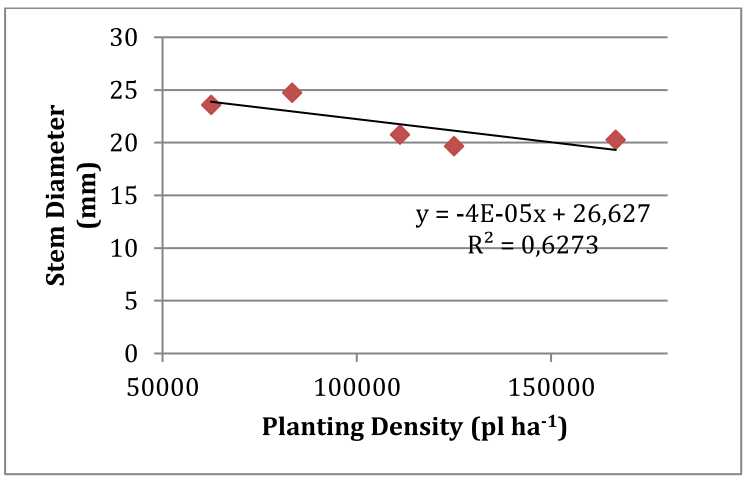
Sources of variation	**DF**	**Plant height**		**Stem diameter**		**Number of leaves**		**Lodging index**	
		2019	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Planting arrangement	4	0.677^{ns}	0.302^{ns}	7.307^{**}	1.602^{ns}	2.836^{ns}	0.627^{ns}	4.779^{**}	0.606^{ns}

Block	4	5.628^{ns}	3.077^{*}	3.525^{*}	0585^{ns}	1.910^{ns}	0.487^{ns}	1.344^{ns}	0.515^{ns}

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

During the first cycle it was observed an inverse relationship between the planting densities and the stem diameter, in which the stem diameter decreases by 14% as the planting density increases, going from 23.6 mm to 20.3 mm (Graphic 1). This effect is certainly related with intra-specific competition, since densely cultivated plots tend to be affected by self-shading, thus reducing photosynthesis and growth (FERREIRA, 2014).

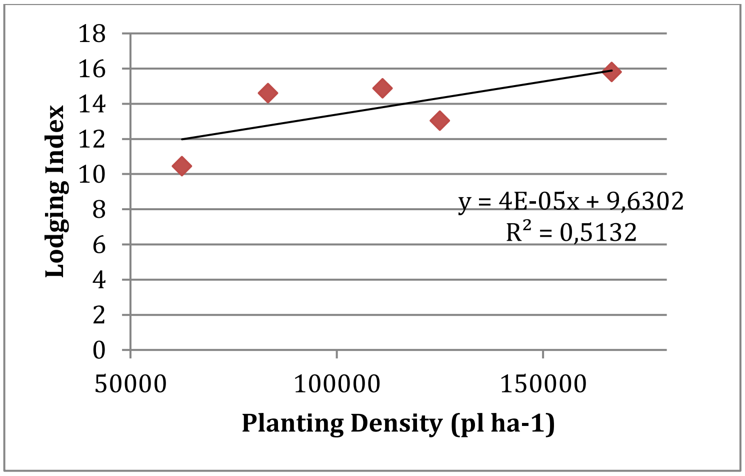
Graphic 1 – Stem diameter (mm) of amaranth *BRS Alegria* plants as a function of the planting density in the first cycle. Pentecoste – CE, 2019 – 2020.



Stem diameter is important because it is directly related with lodging, which is a relatively common phenomenon in grain amaranth and causes significant yield loss for the crop, since it makes harvesting difficult (SILVA et al., 2019).

Concerning the lodging index (Graphic 2), differently from the stem diameter, it was observed a direct relationship between lodging index and planting densities, with a linear increase of 51.2% in the lodging index, when comparing the highest and the lowest densities in the first cycle.

Graphic 2 – Lodging index of amaranth *BRS Alegria* as a function of the planting density in the first cycle. Pentecoste, 2019 – 2020.



Lodging is among the problems associated with excessively high plant populations (ESPITIA-RANGEL, 2018). However, lodging is also related to other factors such as nitrogen fertilization, high winds, genotypes, and planting date (SILVA et al., 2019). Besides the planting density, high winds could 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).

Given that the planting arrangements played no role whatsoever in plant growth during the second cycle, it was to be expected that these factors would also not play a significant role in plant lodging, since the index takes into consideration plant height and stem diameter for its calculation.

5.3.2 Biomass production

The planting densities affected total above ground fresh matter in both years whereas total above ground biomass (dry matter) was affected only during the first year (Table 7). In the second cycle total above ground biomass (dry matter) was in average 10.36 t ha^{-1}.

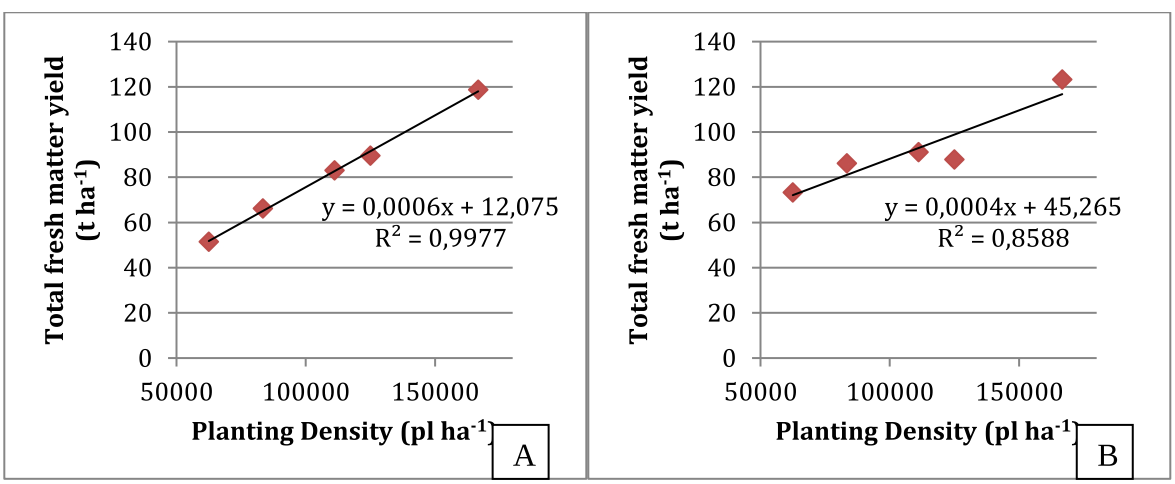
Table 7 - *F*-test results and its level of significance for the biomass accumulation characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement. Pentecoste, CE – 2019 - 2021.

Source of variation	**DF**	**Total fresh matter yield**		**Total above ground biomass (dry matter)**	
		2019	**2020**	**2019**	**2020**
Planting arrangements	4	5.84*	28.70**	5.06**	0.80^{ns}
Block	4	5.58*	3.21*	2.50^{ns}	0.57^{ns}

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

The estimated total fresh matter yield of grain amaranth was favored by the narrow spacings and showed a linear increase (Graphic 3), going from 73.3 t ha^{-1} to 123.2 t ha^{-1}, a 68% increase in the first cycle and from 51.42 t ha^{-1} to 118.74 t ha^{-1}, a 130% increase in the second cycle.

Graphic 3 – Total fresh matter yield (t ha^{-1}) of amaranth *BRS Alegria* as a function of the planting density (pl ha^{-1}). Pentecoste – CE, 2019 – 2020.

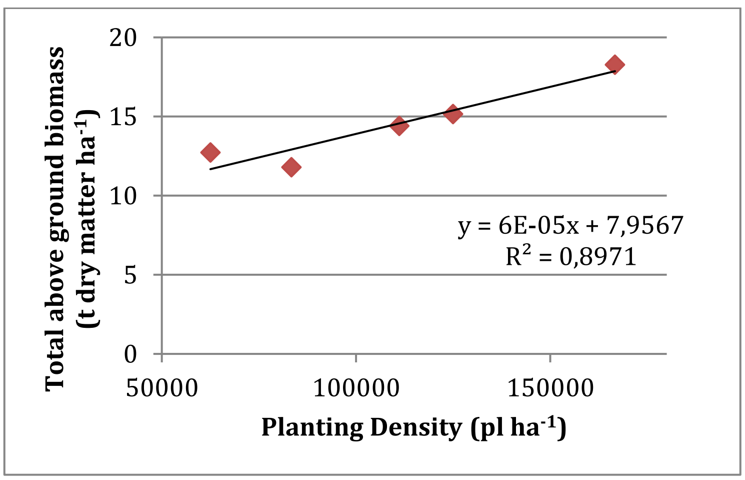


Note: A = 2019; B = 2020.

Grain amaranth's high fresh matter production (above 100 t ha^{-1} for the narrowest planting arrangement) in such a short time (about 75 days from seeding to biomass collection) as well as its inherently high nutritional value, render this pseudo cereal an interesting species to be explored as a source of forage in the Brazilian semi-arid.

The estimated total aboveground biomass (dry matter) showed a significant variation for the first cycle only (Graphic 4), and increased linearly going from 12.73 to 18.29 t ha^{-1}, a 43% increase. During the second cycle, the above ground biomass yield was in average 10.49 t ha^{-1}. As seen for the fresh matter yield, the narrow spacing also resulted in a linear increase and favored a greater dry matter accumulation.

Graphic 4 – Total above ground biomass (t dry matter ha^{-1}) of amaranth *BRS Alegria* as a function of the planting density in the first cycle. Pentecoste – CE, 2019 – 2020.



Gimplinger et al. (2007) reported that total aboveground biomass was not affected by crop density; whereas Henderson, Johnson and Schneiter (2000) report that the greatest biomass yield was produced by the plants at the lowest population. In our study, since row and plant spacing, and therefore plant population, had little significant effect on plant growth, affecting stem diameter only, the greater plant populations allowed for a greater amount of biomass per area.

5.3.3 Yield

Grain yield was affected by the planting densities in both years, harvest index was affected in the second year only and the average harvest index in the first year was (10.39%). The thousand grain weight (TGW) was affected by the densities in the second year only (in the first cycle the one-thousand grain weight was in average 0.635 g) (Table 8).

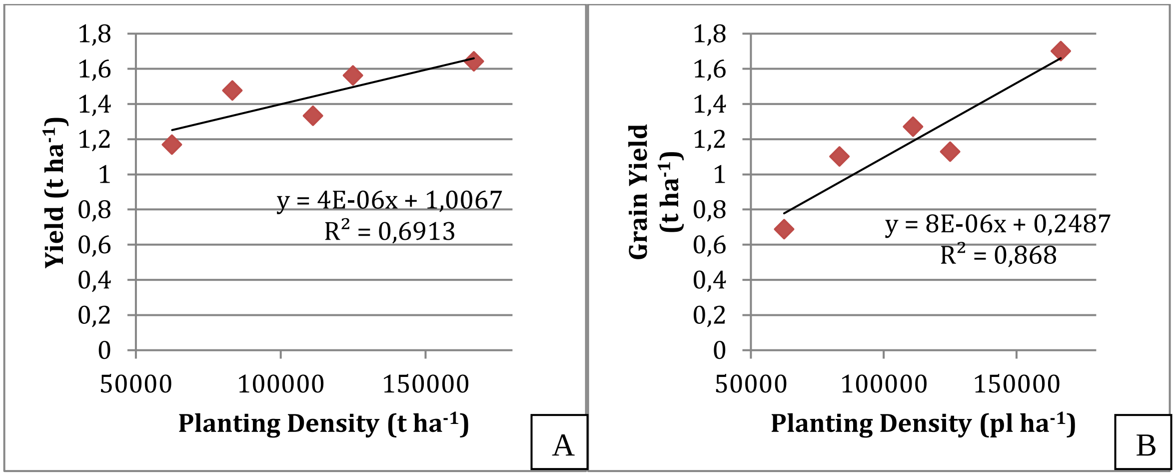
Table 8 - *F*-test results and its level of significance for the yield characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement. Pentecoste, CE – 2019 - 2021.

Source of variation	**DF**	**Yield**		**Harvest index**		**Thousand grain weight (TGW)**	
		2019	**2020**	**2019**	**2020**	**2019**	**2020**
Planting arrangement	4	3.59*	3.819^{*}	2.53^{ns}	5.74^{**}	0.303^{ns}	6.27^{**}
Block	4	0.18^{ns}	0.618^{ns}	2.25^{ns}	0.28^{ns}	0.606^{ns}	0.605^{ns}

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

In both years, the highest yield was obtained in the plots cultivated under the narrowest spacing (Graphic 5). The grain yield increased linearly in a direct relationship to the planting density and the yield difference between the lowest and the highest plant densities were 40 and 150% for the first and the second year, respectively. It was also observed that there was no plateau in the graph, so it is probable that further population increases could also result in yield increases.

Graphic 5 - Grain yield (t ha^{-1}) of amaranth *BRS Alegria* as a function of the planting density. Pentecoste – CE, 2020.

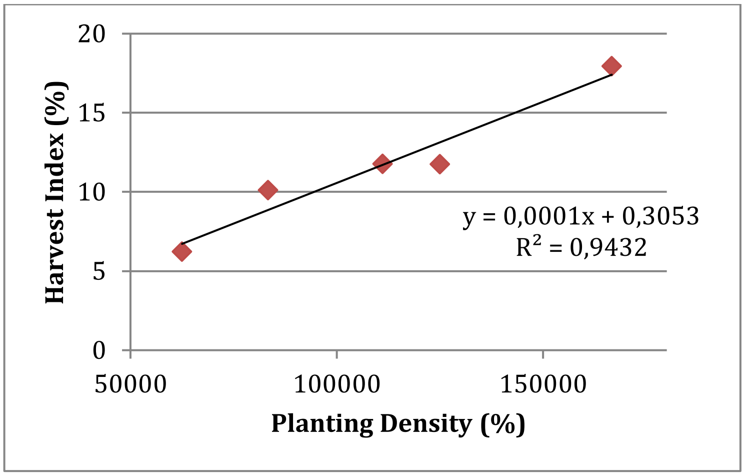


According to Spehar et al. (2003), in the Brazilian Cerrado this crop's yield reached up to 2.3 t ha^{-1} in succession to the soybean crop. Gimplinger et al. (2007) reported yields varying from 2.4 t ha^{-1} to 2.7 t ha^{-1} in Eastern Austria. The inherently limiting environmental conditions imposed 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 (between 0.68 and 1.70 t ha^{-1}).

Concerning the harvest index, in the second cycle it was observed a linear fit of the regression curve with a direct relationship to the planting densities (Graphic 6); therefore the greatest harvest index (17.95%) was observed for the 166,666 pl ha^{-1} density. This indicates that, in the second cycle, as the densities increased the grain production increased to a higher extent than the biomass production does.

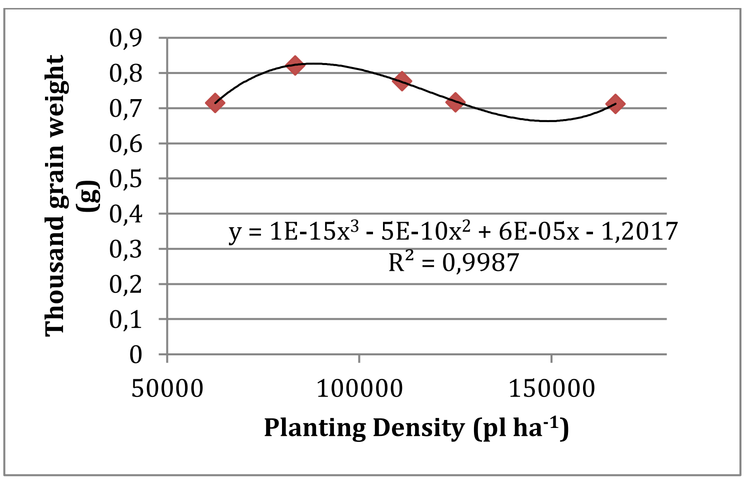
Gimplinger at al. (2007) observed that the harvest index of amaranth responds to rising plant density with decreasing figures.

Graphic 6 – Harvest index (%) of amaranth *BRS Alegria* as a function of the planting density. Pentecoste – CE, 2019 – 2020.



The thousand grain weight was only significant in the second year (Figure 1) and the regression curve presented a cubic curve. The greatest thousand grain weight was observed for the 83,333 pl ha^{-1} density (0.82 g).

Figure 1 – Thousand grain weight (g) of amaranth *BRS Alegria* as a function of the planting density in the second cycle. Pentecoste – CE, 2019 – 2020.



The 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 is able to 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. (2019), Spehar et al. (2003), Pospsil et al. (2006) and Gimplinger et al. (2007), who point out that overall, the TGW value for this species is around 0.7 g.

5.3.4 Grain quality

The lipid content was affected by the planting arrangements in both years (Table 9).

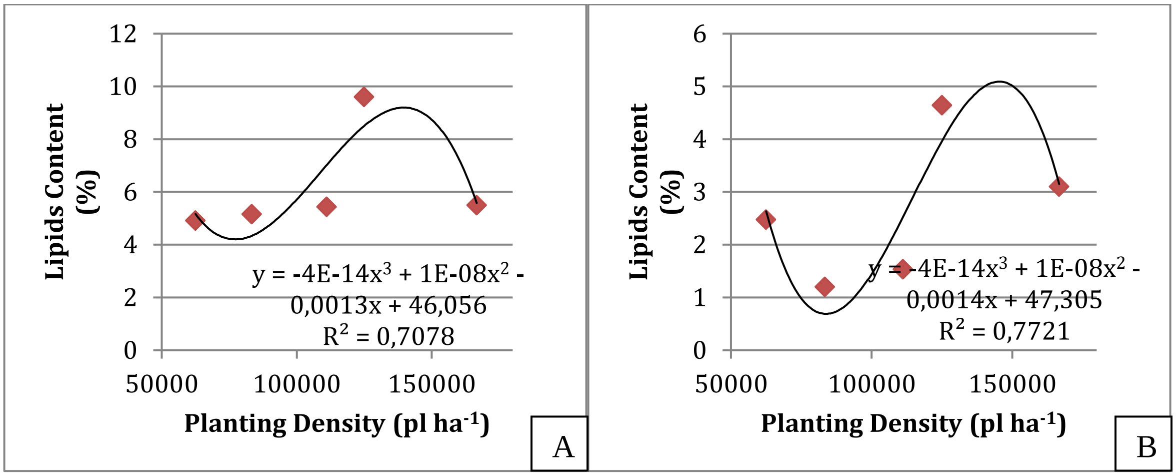
Table 9 - *F*-test results and its level of significance for the quality characteristics of grain amaranth *BRS Alegria* as a function of the planting arrangement. Pentecoste, CE – 2019 - 2021.

		Lipids content	
Source of variation	**DF**	**2019**	**2020**
Row spacing (R)	4	35.91^{**}	12.14^{**}
Block	4	2.49^{ns}	0.66^{ns}

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

In both years, the highest lipid content in the grains was obtained by the plants cultivated in the 40 x 20 cm planting arrangement (Graphic 7). It was also observed that in both cycles there was a sigmoid fit to the regression curve in which the lipids content would decrease slightly as the planting density increase, and then it would grow significantly at the 40 x 20 cm spacing, to then decrease again.

Graphic 7 – Lipids content (%) of grain amaranth *BRS Alegria* as a function of the planting density in the first cycle. Pentecoste – CE, 2019 – 2020.



Note: A = 2019; B = 2020.

Overall, it was observed that the lipid content in the grain tends to increase as plant spacing diminishes, until it reaches a maximum, after that it starts do decrease again. The lipid content is a function of the plant's photosynthetic capacity (SCHMIDT, 2021) and thus is impaired by the competition that results from higher plant populations, and that was also observed here.

Amaranth seeds are reported to contain 5.7 – 9% oil (LYON; BECKER, 1987; VENSUKTONIS; KRAUJALIS, 2013). The values obtained during the first cycle were, therefore, within average.

5.4 Conclusions

1. The evaluated planting arrangements had little effect on grain amaranth's growth affecting stem diameter and plant lodging only.
2. In the Brazilian semi-arid, under the study conditions, amaranth can yield up to 1.7 t ha^{-1} grain and 123.2 t ha^{-1} fresh matter.
3. It was observed that the high plant density favors biomass production and grain yield, therefore the 166,666 pl ha^{-1} could be recommended for the study area.
4. The greatest lipid contents were obtained at 125,000 plants ha^{-1}, and further plant population increase negatively affects the lipids content.

6 CHAPTER II [2] - EFFECT OF SOIL TYPE, AND SOWING DEPTH ON THE GERMINATION AND EARLY GROWTH OF GRAIN AMARANTH CULTIVARS

ABSTRACT

Grain amaranth is a highly nutritional pseudo-cereal with good adaptability to a range of environmental conditions and potential to be further explored in different parts of the world. Germination and initial growth evaluation of plants subject to various conditions are the first step towards understanding a novel crop. The objective with this study was to evaluate how cultivar, sowing depth, and soil type affects emergence and early growth of grain amaranth. A pot experiment was carried out in two runs in a greenhouse. The experiment was set in a randomized complete block design in a 3 x 5 x 2 factorial arrangement with three soil types (loam, clay loam, and clay) x five sowing depths (0, 5, 10, 15, and 20 mm) x two grain amaranth cultivars (*A. cruentus* BRS Alegria and *A. caudatus* Inca). Soil type, sowing depth, and cultivar had a significant effect on germination and early growth of grain amaranth. *A. caudatus* had greater plant height, stem diameter, number of leaves, root length, fresh weight, and dry weight. Emergence was affected by cultivar and was 15% greater for *A. cruentus*. Plant height was significantly greater between 5- and 20 mm deep. Root growth varied as a function of the interaction between soil types and sowing depths in which the longest roots were obtained when grain amaranth was sown in a loam soil at 10 mm depth. For better growth of grain amaranth, the recommended combination is *A. caudatus* in a loam soil at a depth between 5- and 20 mm.

6.1 Introduction

Grain amaranth (*Amaranthus* spp. L.) is a dicotyledonous pseudo-cereal whose leaves and grains are consumed as food in many parts of the world (VÉLEZ-JIMENEZ et al., 2014). This plant species stands out due to its nutritional value, more specifically the high protein content (15-18%) as well as the lysine and calcium contents in its grains (5.2 and 0.37 g 100 g^{-1},

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[2] Artigo submetido ao periódico *Crop Science* em: 22/08/2022.

respectively) (PETR et al., 2003). Grain amaranth is well adapted to marginal lands and has great potential for a bigger development and adaption due to its high genetic diversity and phenotypic plasticity (ECKER et al., 2010; EMIRE; AREGA, 2012; RASTOGI; SHUKLA, 2013). The combination of these characteristics alongside with its inherent tolerance to high temperatures, droughts, poor soils, and the lack of phytosanitary problems render grain amaranth an interesting crop to be grown under adverse conditions such as the ones expected to occur in a climate change scenario (FUENTES-REYES et al., 2018). Because of its relatively high revenue prices and its ever-growing popularity in the Western world, grain amaranth might represent a stable source of income for farmers in the coming decades (EMIRE; AREGA, 2012).

When studying a new crop or cultivar, the evaluation of the germination and initial growth of plants subjected to different conditions (i.e. soil types, sowing depths, light regimes, air temperature, etc.) is the first step towards understanding the effects of the environment on plant morphology and production (MONTEIRO et al., 2016). Aufhammer et al. (1994), Kauffman (1992), and Webb et al. (1987) reported that edaphoclimatic factors such as soil type, and sowing depth directly affect germination and initial growth of grain amaranth plants.

Seeding depth is crucial for the success of this crop. Under shallow sowing conditions, amaranth germination might be inhibited by light, especially under low air temperature conditions (GUTTERMAN et al., 1992; RODRIGUES et al., 2016). However, because of the low reserves content in its seeds, sowing depth must not be deeper than 20 mm (SANTOS et al., 2019).

Soil type plays an important role in amaranth germination and this role is mainly related with the nature of the soil surface (AUFHAMMER, 1994). Surface soil crusting strongly reduces amaranth emergence (KAUFFMAN; HASS, 1983) and this is a phenomenon of relatively common occurrence in Ohio and many other places around the world. Soil crusting most often occurs when rain separates the soil into very small aggregates and individual particles that cement into hard layers at the soil surface when drying occurs rapidly (LE BISSONNAIS, 1996). Studies aiming to investigate how the growth characteristics of plant species respond to local soils are important to facilitate the development of management practices for greater yield with good quality (HOSSAIN; ISHIMINE, 2005).

Regarding the cultivar choice, it must take into consideration the climate conditions of the region in which grain amaranth will be cultivated. Under temperate climate conditions, given that grain amaranth has a higher demand for heat than moisture, cultivars with a fast development and short growth cycle are preferred to avoid being damaged by early frosts (DMITRIEVA; IVANOV, 2020). The *A. cruentus* BRS Alegria cultivar was developed by the Brazilian Agricultural Research Corporation (Embrapa) and is reported to have achieved, in a 90-day crop cycle, a grain yield of up to 2.3 t ha^{-1} and up to 5.6 t ha^{-1} of total dry biomass (FERREIRA et al., 2014). The *A. caudatus* Inca variety has been reported to achieve up to 1.5 t ha^{-1} grain yield in a 63-day crop cycle (SILVA et al., 2019) and was selected for this study because of its morphological characteristics, that differ in relation to *A. cruentus*, i.e. growth habit, inflorescence shape, leaf color, etc.

Thus, the objective of of this study was to evaluate sowing depth, soil type, and cultivar effect on seedling emergence and early growth of two grain amaranth cultivars grown under greenhouse conditions.

6.2 Materials and methods

One pot experiment was carried out in two runs at the Howlett Greenhouse, belonging to the Department of Horticulture and Crop Science at the Ohio State University, aiming to evaluate seedling emergence and early growth of two grain amaranth cultivars (*Amaranthus cruentus* L. BRS Alegria cultivar and *Amaranthus caudatus* Inca variety) grown in three soils (clay loam, loam, and clay) and five sowing depths (0, 5, 10, 15, and 20 mm).

The experiment was set up in a randomized complete block design in a 3 x 5 x 2 factorial arrangement (three soil types x five sowing depths x two grain amaranth cultivars) with four replications and two runs. Data from the two runs were analyzed jointly using the GLIMMIX procedure through SAS Studio® version 9.4. Residual normality was assessed for ANOVA. Fixed effects were cultivar, soil type, sowing depth and the interactions between the three factors. Replication and run were the random effects. During analysis, degrees of freedom were calculated to determine the number of final independent values that could vary at a significance level of 5% (α = 0.05). When a global f-test was found to be significant, means were separated using PROC GLIMMX p-values for differences (PDIFF) of the least significant means (LSM) tests for pairwise comparisons. Significant differences among the means were determined using the Tukey test at .05 significance level.

Before the establishment of the experiments a warm germination test was performed using 60 seeds of each cultivar under moist conditions on rolled paper towels at 25ºC in the absence of light according to the methodology described by Donazzolo et al. (2017). The germination of the seed batches used for the greenhouse trials ranged between 80 (*A. caudatus* Inca) and 93% (*A. cruentus* BRS Alegria) while the thousand seed weight varied between 0.6 (*A. cruentus* BRS Alegria) and 0.8 g (*A. caudatus* Inca). The lower germination rate obtained by *A. caudatus* is probably related to its storage time - *A. caudatus* had been stored for two years, whilst *A. cruentus* had been stored for one year only. According to Kehinde et al. (2013) storage under ambient conditions should not exceed 3 months for best performance of amaranth seeds.

Before setting up the experiment, soil was collected with a soil probe from three different locations in Ohio (Loam soil: 39° 51’ 41.40” N, 83° 40’ 30.36” W; Clay soil: 41° 13’ 6.6” N, 83° 45’ 48.24”W; Clay loam: 39˚51’48.848” N, -83˚40’34.993” W) at the 0-20 cm depth, then chemical and physical properties were measured as shown in Table 10. These soils have a history of being used for agricultural purposes, with a history of maize-soybean rotation. Before seeding, the soil was homogenized and sieved in 5 mm sieves. Then, five undamaged seeds of amaranth were broadcast in each cell and covered with an appropriate depth of soil of the same texture.

Table 10 - Physical and chemical properties of the three soils used in the experiment.

Soil[a]/Series	Organic Matter	P	K	Magnesium	Calcium	Soil pH	Cation Exchange Capacity	Sand	Silt	Clay
	(%)	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})		(meq $100g^{-1}$)	(%)	(%)	(%)
Clay loam/ (Kokomo)[1]	4.5	41	192	577	2,273	6.0	20.3	26	42	32
Loam/ (Strawn-Crosby)[2]	3.4	22	101	559	2,174	7.4	15.8	28	48	24
Clay/ (Hoytville)[3]	4.4	25	198	414	2,816	6.7	19.2	26	30	44

[a] Soil was collected at 0-20 cm depth from fields under crop production.

[1] Fine, mixed, superactive, mesic Typic Argiaquolls

[2] Fine-loamy, mixed, active, mesic Typic Hapludalfs / Fine, mixed, active, mesic Aeric Epiaqualfs

[3] Fine, illitic, mesic Mollic Epiaqualfs

6.2.1 Experiment set up

The trials were carried out in plastic trays (Greenhouse Megastore™) containing cells with 156 cm^3 volume each (6 x 6.5 x 4 cm), in which each cell corresponded to one experimental unit. Five seeds of the corresponding cultivar were sown in each cell.

The plastic trays were then placed in a greenhouse bench and were watered through a misting system that was programmed to sprinkle for 10 seconds every 15 minutes, ensuring that the soil in the trays was kept at field moisture capacity. The temperature in the greenhouse was set to 25°C during the experimental period. The plants received supplementary lighting for 12 h, due to the shading conditions of the greenhouse. The seedlings (tops and roots) were harvested at 15 days after sowing (DAS) (methodology adapted from BAVEC; MLAKAR, 2012).

6.2.2 Evaluations

At the end of each run, the number of emerged seedlings was evaluated and the values resulting from germination differences among species were corrected to percentage of live (germinated) seedlings emergence (PLSE). Those seeds that originated seedlings with fully emerged, well-formed and free from infection tops were considered as germinated (BRASIL, 1992).

At 15 days after sowing, seedlings were harvested, and the roots were washed and dried. Following, plant height and root length were measured with a ruler and the stem diameter was determined with a digital caliper (Fisher Scientific Traceable ®). The number of leaves was also counted. After those measurements, the seedling fresh weight was determined. Following, the seedlings were placed in paper bags and their dry weight was measured after drying in an oven (VWR™ Scientific 1370G Gravity Convection Oven) at 65°C until constant weight.

6.3 Results and discussion

All the emergence and early growth characteristics evaluated for grain amaranth varied significantly as a function of the cultivar (Table 11). Plant height also varied as a function of the sowing depth, and the root length also varied as a function of the interaction between soil types and sowing depths.

Table 11 - ANOVA table

Effect	PLSE (%)	Plant height (cm)	Stem diameter (mm)	Number of leaves	Root length (cm)	Fresh weight (mg)	Dry weight (mg)
	p-value						
Soil type (S)	0.125	0.572	0.317	0.274	0	0.075	0.17
Cultivar (C)	0.001	0.005	0	<.000	<.000	<.000	0.015
Sowing depth (SD)	0.242	<.000	0.29	0.301	0.093	0.642	0.709
S * X	0.631	0.448	0.527	0.689	0.31	0.038	0.212
S * SD	0.726	0.68	0.296	0.416	0.05	0.322	0.119
SD * C	0.577	0.825	0.241	0.192	0.761	0.82	0.612
S * SD * C	0.665	0.404	0.124	0.812	0.409	0.576	0.296

LSE= Percentage of live seedlings emergence

Regarding the cultivars, it was observed that *Amaranthus caudatus* Inca obtained greater plant height, stem diameter, number of leaves, root length as well as fresh and dry weight, differing significantly from the values obtained by the *A. cruentus* BRS Alegria cultivar (Table 12). The *A. cruentus* only stood out in terms of emergence, being 14.50% higher than *A. caudatus*.

Concerning grain amaranth’s germination and emergence, Bavec & Mlakar (2002) reported 48 % PLSE for *A. caudatus* and 31 % PLSE for *A. cruentus* while Santos et al. (2019) obtained an average of 71 % emergence for *A. cruentus* BRS Alegria and 47 % emergence for *A. caudatus* Inca, and the recommended sowing depth was 10 mm.

In previous studies (DA SILVA et al., 2019; SANTOS et al., 2019) it has been observed that the *A. caudatus* Inca has faster growth and completes its productive cycle in a shorter time than *A. cruentus*. It could be related with the higher content of reserves found in its seeds (weighing 0.8 g against 0.6 g from *A. cruentus*), which allows for a faster initial growth, resulting in more vigorous seedlings.

Table 12 - Emergence and early growth characteristics of grain amaranth as a function of the cultivar

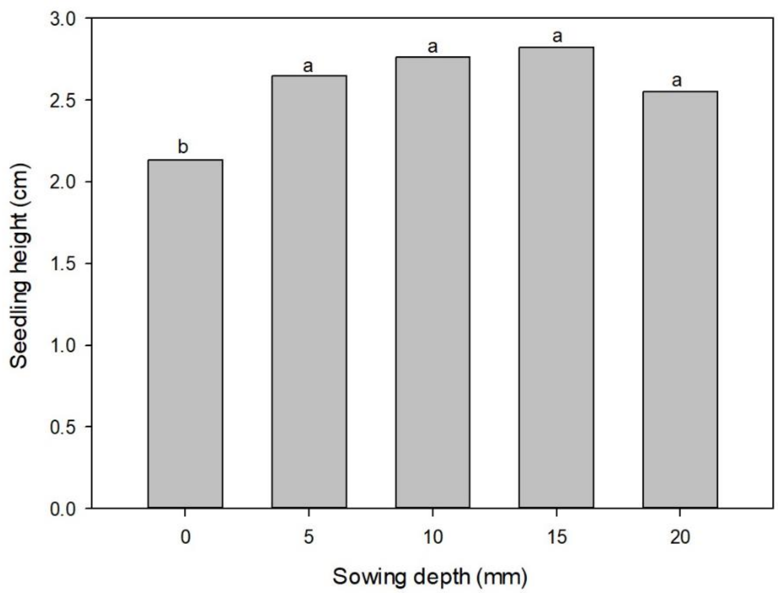
Cultivar	PLSE	Plant height	Stem diameter	Number of leaves	Root length	Fresh weight	Dry weight
	(%)	(cm)	(mm)		(cm)	(mg)	(mg)
A. caudatus	61.10 b	2.71 a	0.51 a	2.55 a	3.25 a	34.59 a	3.85 a
A. cruentus	75.60 a	2.45 b	0.47 b	2.29 b	2.71 b	24.07 b	3.13 b

Means followed by the same letter in the same column do not differ statistically among themselves by the Tukey test ($\alpha < .05$)

PLSE= Percentage of live seedlings emergence.

Grain amaranth’s plant height was also influenced by the sowing depth (Figure 1). The 0 mm depth produced the shortest plants whereas the 15 mm depth resulted in the greatest plant height, although it did not differ statistically from the 5-, 10- and 20-mm depth. Even though the 20 mm depth resulted in a plant height statistically similar to the other depths, a decreasing trend can be observed, and it can therefore be supposed that further increases in depth could result in decreases in plant height. Da Silva et al. (2019) reported a greater plant height for *A. cruentus* BRS Alegria sown at 10 mm depth in comparison to the 20 mm depth.

Graphic 8 - Plant height (cm) of grain amaranth as a function of the sowing depth



Means followed by the same letter do not differ statistically among themselves by the Tukey test (α < .05).

In this study, the root length of grain amaranth varied as a function of the interaction between soil types and sowing depths (Table 5). For both the loam and the clay soils the 10 mm depth produced the longest roots. The shortest roots were observed for the clay loam soil at 0 mm depth. It was also observed that the lighter soil (loam) favors a greater root development, and that the clay loam soil tends to hinder root development.

Table 13 - Root length (cm) of grain amaranth as a function of the interaction between soil type and sowing depth (mm)

Soil type	Sowing Depth (mm)	Root length (cm)
Loam	0	3.20 abc
	5	3.01 abc
	10	3.49 a

	15	3.31	ab
	20	3.17	abc
Clay	0	2.85	abcd
	5	3.25	abc
	10	3.45	a
	15	2.79	bcd
	20	3.11	abc
Clay loam	0	2.01	e
	5	2.59	cde
	10	2.38	de
	15	2.80	abcd
	20	3.26	abc

Means followed by the same letter do not differ statistically among themselves by the Tukey test ($\alpha < .05$).

Overall, it was observed that the genotype, here represented by the two evaluated cultivars, has a greater influence on grain amaranth’s emergence and early growth than soil type and sowing depth. Soil type and sowing depth appear to play a role in favoring or hindering tissue elongation, as observed by the significant effect of these factors on plant height and root length.

Finally, this study shows that, under the study conditions, better initial growth of amaranth is achieved by *A. caudatus*. Sowing between 5 and 20 mm allows for better growth. The use of either loam or clay soil and sowing at 10 mm depth allows for better root development in early growth of grain amaranth.

6.4 Final considerations

Grain amaranth proved to be a suitable crop to be grown in the Brazilian semi-arid. The analysis of the results showed that the 30x20 planting arrangement was the most suitable for the cultivation of this crop in the Brazilian semi-arid, in terms of grain and biomass yield as well as grain quality. However, it was also observed that narrow spacings favor a higher incidence of plant lodging. Under the experimental conditions approached here, plant growth was not significantly affected by the planting arrangements.

Under controlled environment conditions, it was observed that the *Amaranthus caudatus* species stood out for almost all of the studied parameters. The sowing depth for this crop should be performed in any depth between 5 and 20 mm deep. Among the soil types evaluated, the loam and clay soils allowed for better root growth. It could be deduced that the cultivation of *A. caudatus*, preferably in a loam or clay soil, sown at either at 5, 10, 15 or 20 mm deep will allow for a better crop establishment.

These results provide valuable information for farmers interested in diversifying their agricultural businesses by adopting an emerging crop with high revenue value and high tolerance to restrictive environmental conditions (i.e. droughts, high temperatures, etc.). These results are also provide valuable information for researchers interested in broadening the knowledge on the cultivation of grain amaranth in the Brazilian semi-arid or in the United States' Mid-West, since it provides them with basic knowledge on this crop's management.

BIBLIOGRAPHICAL REFERENCES

ACHIGAN-DAKO, E. G.; SOGBOHOSSOU, O. E. D.; MAUNDU, P. Current knowledge on *Amaranthus* spp.: research avenues for improved nutritional value and yield in leafy amaranths in sub-Saharan Africa. **Euphytica**, Amsterdam, v. 197, p. 303–317, 2014.

ADHIKARY, D.; PRATT, D. B. Morphologic and taxonomic analysis of the weedy and cultivated *Amaranthus hybridus* species complex. **Systematic Botany.** v. 40, p. 604–610, 2015.
ALBA, E.; POLIGNANO, G.B.; NOTARNICOLA, L. Yield stability in a set of amaranth entries in Southern Italy. **Italian Journal of Agronomy**, Pavia, v.1, n. 2, p. 65–71, 1997.

ALEMAYEHU, F.; BENDEVIS, M.; JACOBSEN, S-. E. The Potential for Utilizing the Seed Crop Amaranth (*Amaranthus* spp.) in East Africa as an Alternative Crop to Support Food Security and Climate Change Mitigation. **Journal of Agronomy and Crop Science**, London, v. 201, n. 5, 321-329, 2015.

ALVAREZ-JUBETE, L.; WIJNGAARD, H.; ARENDT, E. K.; GALLAGHER, E. Polyphenol composition and in vitro antioxidant activity of amaranth, quinoa buckwheat and wheat as affected by sprouting and baking. **Food Chemistry**, Amsterdam, v. 119. p. 70–778, 2010.

ANSARIARDALI, S.; AGHAALIKHANI, M. Effect of nitrogen and density on qualitative and quantitative performance of forage Amaranth. **Iranian Journal of Agronomy Science**, Tehran, v. 1, p. 35-40, 2013.

APAZA-GUTIERREZ, V.; ROMERO-SARAVIA, A.; GUILLEN-PORTAL, F. R.; BALTENSPERGER, D. D.; Response of grain amaranth production to density and fertilization in Tarija, Bolivia. In: JANICK, J.; WHIPKEY, A. (Org.), **Trends in New Crops and New Uses.** ASHS Press, Alexandria, VA, p. 107–109, 2002.

ARAUS, J. L.; GUSTAVO, A. S.; CONXITA, R.; DOLORES, M. S. Breeding for Yield Potential and Stress Adaptation in Cereals. **Critical Reviews in Plant Science**, London, v. 27, p. 377–412, 2008.

AUFHAMMER, W.; KAUL, H.-P.; KRUSE, M.; LEE, J. H.; SCHWESIG, D. Effects of sowing depth and soil conditions on emergence of amaranth and quinoa. **European Journal of Agronomy**, Amsterdam, v. 3, n. 3, p. 205–210, 1994.

AUFHAMMER, W.; KÜBLER, E. Vergleichende Untersuchungen zur Anbauwürdigkeit der Getreidearten Rispenhirse (*Panicum milleaceum*) und Kanariensaat (*Phalaris canariensis*) sowie der Pseudogetreidearten Buchweizen (*Fagopyrum esculentum*), Reismelde (*Chenopodium quinoa*) und Amaranth (*Amaranthus* sp.). **Die Bodenkultur**, Warsaw, v. 49, n. 3, p. 159–169, 1998.

AYNEHBAND, A. Cultivar and nitrogen splitting effects on amaranth forage yield and weed community. **Pakistan Journal of Biological Science**, Dubai, v. 11, p. 80-85, 2008.

BALLABIO, C.; UBERTI, F.; DI LORENZO, C.; BRANDOLINI, A.; PENAS, E.; RESTANI, P. Biochemical and immunochemical characterization of different varieties of Amaranth (*Amaranthus* L. ssp.) as a safe ingredient for gluten-free products**. Journal of Agricultural and Food Chemistry**, Washington, v. 59, n. 129, p. 69-74, 2011.

BANZATO, D. A.; KRONKA, S. do N. **Experimentação agrícola**. 4.ed. Jaboticabal: Funep, 2006. 237p.

BAVEC, F.; MLAKAR, S. G. Effects of soil and climatic conditions on emergence of grain amaranths. **European Journal of Agronomy**, Amsterdam, v. 17, n. 2, p. 93-103, 2002.

BERGANZA, B. E.; MORAN, A. W.; RODRIGUEZ, M. G.; COTO, N. M.; SANTAMARIA, M.; BRESSANI, R. Effect of variety and location on the total fat, fatty acids and squalene content of Amaranth. **Plant Foods for Human Nutrition**, Geneva, v. 58, p. 1-6, 2003.

BERGER, A.; GREMAUD, G.; BAUMGARTNER, M.; REIN, D.; MONNARD, I.; KRATKY, E. Cholesterol-lowering properties of Amaranth grain and oil in hamsters. **International Journal of Vitamin and Nutrition Research**, Newburyport, v. 73, p. 39-47, 2003.

BESWA, D.; DLAMINI, N. R.; SIWELA, M.; AMONSOU, E. O.; KOLANISI, U. Effect of Amaranth addition on the nutritional composition and consumer acceptability of extruded provitamin A-biofortified maize snacks. **Journal of Food Science and Technology**, [*s.l.*], v. 36, p. 30–39, 2016.

BIANCHINI, M. G. A.; BELÉIA, A. D. P. Umidade e congelamento de grãos de amaranto e sua capacidade de expansão térmica. **Pesquisa Agropecuária Brasileira**, Brasília, v. 45, n. 8, p. 917-924, 2010.

BRASIL - MINISTÉRIO DA AGRICULTURA. **Regras para análise de sementes.** Brasília: SNAD/DNPV/CLAV, 1992. 365 p.

BRASIL, Ministerio da Ciência, Tecnologia e Inovação (MCTI). **Modelagem climatica e vulnerabilidades Setoriais a mudanca do clima no Brasil,** 2016a. Disponível em: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/cgcl/clima/arquivos/modelagem-climatica-e-vulnerabilidades-setoriais-a-mudanca-do-clima-no-brasil/mcti-livromodelagemclimatica-edicaao-eletroenica-31mai2016_baixa_resolucaao.pdf Acesso em: 27 jan. 2022.

BRASIL, Ministério do Meio Ambiente. **Plano Nacional de Adaptação à Mudança do Clima: volume 2: estratégias setoriais e temáticas**, 2016b. Disponível em: https://www4.unfccc.int/sites/NAPC/Documents/Parties/Brazil/Brazil%20PNA_%20Volume%202.pdf Acesso em: 27 jan. 2022.

BRENNER, D. Genetic resources and breeding of amaranthus. **Plant Breeding Reviews**, [*s.l.*], v. 19, p. 227-286, 2000.

BRESSANI, R. **Composition and nutritional properties of amaranth.** Amaranth biology, chemistry, and technology. CRC Press, p. 185-205, 2018.

BRESSANI, R.; ELIAS, L. G. **Development of 100% Amaranth Foods**. In: Proc. Third Amaranth Conf. Rodale Press, Inc., Emmaus, PA. 1987.

CASINI, P; BIANCOFIORE, G. Influence of row spacing on canopy and seed production in grain amaranth (*Amaranthus cruentus* L.). **Journal of Agronomy Research**, [*s.l.*], v. 18, p. 53-62, 2020.

CAVICCHIOLI, R.; RIPPLE, W. J., TIMMIS, K. N.; AZAM, F.; BAKKEN, L. R.; BAYLIS, M. Scientists' warning to humanity: microorganisms and climate change. **Nature Reviews Microbiology**, [*s.l.*], v. 17, n. 5, p.69–86, 2019.

CHENG, A. Review: Shaping a sustainable food future by rediscovering long-forgotten ancient grains. **Plant Science**, Amsterdam, v. 269, p. 136-142, 2018.

COELHO, L. M.; SILVA, P. M.; MARTINS, J. T.; PINHEIRO, A. C.; VICENTE, A. A. Emerging opportunities in exploring the nutritional/functional value of amaranth. **Food & Function Journal**, London, v. 9, n. 11, p. 5499-5512, 2018.

COLE, J. N. **Amaranth**: from the Past, for the Future, Rodale Press, Emmaus, PA, 1979. 311p.
CONAB. **Série Histórica das Safras**. Disponível em: https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras. Acesso em: 27 agosto 2021.

COSTA, D. M. A.; LIMA, M. P. Produtividade do Amaranto (*Amaranthus* spp.) sob adubação orgânica. **Bioscience Journal**, Oxford, v. 26, n. 5, p. 683-691, 2010.

COSTEA, M.; BRENNER, D. M.; TARDIF, F. J.; TAN, Y. F.; SUN, M. Delimitation of *Amaranthus cruentus* L. and *Amaranthus caudatus* L. using micromorphology and AFLP analysis: An application in germplasm identification. **Genetic Resources and Crop Evolution**, New York, v. 53, p. 1625–1633, 2006.

CRIVELARI-COSTA, P. M.; BIANCHINI, A. Malte de variedades de amaranto. **Nativa**, Cuiabá, v. 9, n. 5, p. 563-566, 2021.

D'ODORICO, P.; BHATTACHAN, A.; DAVIS, K. F.; RAVI, S.; RUNYAN, C. W. Global desertification: Drivers and feedbacks. **Advances in Water Resources**, Amsterdam, v. 51, p. 326-344, 2013.

DA SILVA, A. L.; BIANCHINI, A.; SANTOS, M.; CRIVELARI COSTA, P.; PEREIRA, P. Emergence, and initial development of amaranth (*Amaranthus cruentus* l.) BRS alegria at different depths of seeding and water availability. **Journal of Experimental Agriculture International**, Cambridge, v. 41, n. 2, p. 1-9, 2019.

DAS, S. **Future Prospects in Amaranth Research**. In: SAUBHIK, D. (Ed.) Amaranthus: A Promising Crop of Future, p. 167–172, 2016.

DELANO-FRIER, J. P.; AVILES-ARNAUT, H.; CASARRUBIAS-CASTILLO, K.; CASIQUE-ARROYO, G.; CASTRILLON-ARBELAEZ, P. A.; HERRERAESTRELLA, L.; MASSANGE-SÁNCHEZ, J.; MARTÍNEZ-GALLARDO, N. A.; PARRA-COTA, F. I.; VARGAS-ORTIZ, E.; ESTRADA-HERNÁNDEZ, M. G. Transcriptomic analysis of grain amaranth (*Amaranthus hypochondriacus*) using 454 pyrosequencing: comparison with *A. tuberculatus,* expression profiling in 39 stems and in response to biotic and abiotic stress. **BMC Genomics**, v. 12, n. 363, 2011.

DELGADO, J. A.; PETER, M.; GROFFMAN, M.; NEARING, A.; GODDARD, T.; REICOSKY, D.; RATTAN, L.; NEWELL, R. K.; CHARLES, W. R.; DAN, T.; PAUL, S. Conservation practices to mitigate and adapt to climate change. **Journal of Soil and Water Conservation**, Des Moines, v. 66, p. 118–129, 2011.

DMITRIEVA, O.; IVANOV, S. Comparative study of amaranth species (*Amaranthus* spp.) in the temperate continental climate of Russian Federation. **Acta Agriculturae Slovenica**, Ljubljana, v. 115, n. 1, p. 15-24, 2020.

DONAZZOLO, J.; POSSENTI, J. C.; GUOLLO, K.; DANNER, M. A.; BELLE, I. C. Germination of amaranth seeds under influence of light, substrate, and temperature. **Journal of Agroveterinary Sciences**, Joinville, v. 16, n. 2, p. 90-194, 2017.

ECKER, O.; WEINBERGER, K.; QAIM, M. Patterns and determinants of dietary micronutrient deficiencies in rural areas of East Africa. **African Journal of Agricultural and Resource Economics**, Nairobi, v. 4, n. 2, p. 175–194, 2010.

EMBRAPA - EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - Centro Nacional de Pesquisa de Solos. **Sistema Brasileiro de Classificação de Solos**. 3ª ed. Brasília-DF, 2013. 353p

EMBRAPA. Centro Nacional de Pesquisa de Agroindústria Tropical. **Dados climatológicos**: Estação de Pentecoste, 2000; Fortaleza: Embrapa Agroindústria Tropical/UFC, 2001. 14 p.

EMIRE, S. A.; AREGA, M. Value added product development and quality characterization of amaranth (*Amaranthus caudatus* L.) grown in East Africa. **African Journal of Food Science and Technology**, [*s.l.*] v. 3, n. 6, p. 129–141, 2012.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA). Centro Nacional de Pesquisa de Solos. **Sistema brasileiro de classificação de solos.** 3ª ed. Brasília-DF, 2013. 353p.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA). **Zoneamento Agroecológico**; Sistemas Integrados de Produção. 2017.

ESPITIA-RANGEL, E. Breeding of grain amaranth. In:______. **Amaranth biology, chemistry, and technology.** CRC press, p. 23-38, 2018.

FACCIOLA, S. **Cornucopia** - A Source Book of Edible Plants. Kampong Publications, 1990. 677p.

FERREIRA, C. C.; RIBEIRO JUNIOR, W. Q.; RAMOS, M. L. G.; SPEHAR, C. R.; FARIAS, T. R. R. Efeito da densidade de semeadura e doses de nitrogênio sobre a produtividade e biometria de amaranto, no cerrado do planalto central. **Bioscience Journal**, Oxford, v. 30, n. 5, p. 534-546, 2014.

FERREIRA, D. F. SISVAR: A computer analysis system to fixed effects split plot type designs. **Revista Brasileira de Biometria**, Lavras, v. 37, n. 4, p. 529-535, 2019.

FITTERER, S. A.; JOHNSON, B. L.; SCHNEITER, A. A. Grain amaranth harvest timeliness in eastern North Dakota. In: JANICK, J. (Ed.), **Progress in New Crops.** ASHS Press, Alexandria, VA, 220–223, 1996.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). **FAO and Traditional Knowledge**: The Linkages with Sustainability, Food Security And Climate Change Impacts. FAO, Rome, Italy, 2009. 16p.

FRANKE, W. **Nutzpflanzenkunde**: Nutzbare Gewächse der gemäßigten Breiten, Subtropen und Tropen. Thieme, Stuttgart, 1997.

FRISON, E. A. BIODIVERSITY AND LIVELIHOODS. IN: S. BALA R.; HOESCHLE Z.I.; SWAMINATHAN, M. S.; FRISON, E. (Eds.) **Hunger and Poverty**: The Role of Biodiversity Report on an International Consultation on the Role of Biodiversity in Achieving the UN Millennium Development Goals of Freedom from Hunger and Poverty. M.S. Swaminathan Research Foundation, Chennai, India, 18–19, Abril 2005.

FUENTES-REYES, M.; CHÁVEZ-SERVÍN, J. L.; GONZÁLEZ-CORIA, C. Comparative account of phenolics, antioxidant capacity, α-tocopherol and anti-nutritional factors of amaranth (*Amaranthus hypochondriacus*) grown in the greenhouse and open field. **International Journal of Agriculture and Biology**, Faisalabad, v. 20, n. 11, p. 2428-2436, 2018.

FUJIMORI, S.; HASEGAWA, T.; KREY, V.; RIAHI, K.; BERTRAM, C.; BODIRSKY, B.; BOSETTI, V.; CALLEN, J.; DESPRÉS, J.; DOELMAN, J.; DROUET, L.; EMMERLING, J.; FRANK, S.; FRICKO, O.; HAVLÍK, P.; HUMPENÖDER, F.; KOOPMAN, J.; MEIJL, H.; OCHI, Y.; VUUREN, D. A multi-model assessment of food security implications of climate change mitigation. **Nature Sustainability**, London, v. 2, p. 386-396, 2019.

GALLEGOS-INFANTE, J. A.; ROCHA-GUZMAN, N. E.; GONZALEZ-LAREDO, R. F.; OCHOA-MARTÍNEZ, L. A.; CORZO, N.; BELLO-PEREZ, L. A. Quality of spaghetti pasta containing Mexican common bean flour (*Phaseolus vulgaris* L.). **Food Chemistry**, Amsterdam, v. 119, p. 1544–1549, 2010.

GANDHI, P.; KHAN, Z.; NIRAJ, K. In vitro assay of anti-proliferative potential of *Amaranthus cruentus L.* aqueous extract on human peripheral blood lymphocytes. **Current Trends in Biotechnology and Chemical Research**, Mullana, v. 1, p. 42-48, 2011.

GIMPLINGER, D. M.; DOBOS, G.; SCHÖNLECHNER, R.; KAUL, H-. P. Yield and quality of grain amaranth (*Amaranthus* sp.) in Eastern Austria. **Plant Soil and Environment**, Prague, v. 53, n. 3, p. 105–112, 2007.

GUILLEN-PORTAL, F. R.; BALTENSPERGER, D. D.; NELSON, L. A. Plant population influence on yield and agronomic traits in 'Plainsman' grain amaranth. In: JANICK, J. (Ed.), **Perspectives on New Crops and New Uses**. ASHS Press, Alexandria, VA, p. 190–193, 1999.

GUIMARÃES, V. N. **Desempenho agronômico de Amaranto BRS Alegria em diferentes densidades populacionais**. Brasília: Faculdade de Agronomia e Medicina Veterinária, Universidade de Brasília, 2013, 31p.; Monografia; 2013.

GUTTERMAN, Y.; CORBINEAU, F.; CÔME, D. Interrelated effects of temperature, light and oxygen on *Amaranthus caudatus* L. seed germination. **Weed Research**, [*s.l.*] v. 32, n. 2, p. 111–117, 1992.

HABER, T.; OBIEDZIŃSKI, M.; WASZKIEWICZ-ROBAK, B.; BILLER, E.; ACHREMOWICZ, B.; CEGLIŃSKA, A. Pseudocereals and the possibilities of their application in food technology, General characteristics of Quinoa. **Polish Journal of Applied Sciences**, Lomza, v. 3, p. 57–65, 2017.

HAVILAH, E. J. Forages and pastures: annual forage and pasture crops—establishment and management. In: FUQUAY, J.W.; FOX, P.F.; MCSWEENEY, P.L.H. (Org.), **Encyclopedia of Dairy Sciences**, vol. 2, 2nd ed. Academic Press, Oxford, UK, p. 563–575, 2011.

HE, H. P.; CAI, Y.; SUN, M.; CORKE, H. Extraction and purification of squalene from amaranth grain. **Journal of Agricultural and Food Chemistry**, Washington, v. 50, n. 3, p. 68-72, 2002.

HENDERSON, T. L.; JOHNSON, B. L.; SCHNEITER, A. A. Row spacing, plant population, and cultivar effects on grain amaranth in the northern Great Plains. **Agronomy Journal**, Madison, v. 92, p. 329–336, 2000.

HOSSAIN, M. A.; ISHIMINE, Y. Growth, yield and quality of turmeric (*Curcuma longa* L.) cultivated on dark-red soil, gray soil and red soil in Okinawa, Japan. **Plant Production Science**, Tokyo, v. 8, n. 4, p. 482–486, 2005.

IGBOKWE, P. E.; HOLLINS, S. Response of vegetable amaranth to plant spacing. **Journal of Vegetable Crop Production**, London, v. 6, n. 2, p. 75–85, 2000.

INSTITUTO ADOLFO LUTZ. **Normas Analíticas do Instituto Adolfo Lutz.** Métodos físico-químicos para análises de alimentos. 4ª ed. (1ª Edição digital), 2008. 1020p.

JACOBSEN, S. E.; MUJICA, A.; ORTIZ, R. The global potential for quinoa and other Andean crops. **Food Review International**, v. 19, p. 139–148, 2003.

JACOBSEN, S.-E.; SØRENSEN, M.; PEDERSEN, S. M.; WEINER, J. Feeding the world: genetically modified crops versus agricultural biodiversity. **Agronomy for Sustainable Development**, v. 33, p. 651–662, 2013.

JAMRISKA, P. Vplyv odrôd na úrodu semena láskavca (*Amaranthus* sp.). **Rostlinná Vyroba**, Prague, v. 42, n. 3, p. 109–114, 1996.

JAMRISKA, P. Vplyv odrody na medziriadkovej vzdialenosti na ˆstrukt´uru porastu áurodu semena láskavca. **Pol'nohospodárstvo**, Warsaw, v. 48, n. 7, p. 380–388, 2002.

JIMOH, M. O.; AFOLAYAN, A .J.; LEWU, F. B. Suitability of *Amaranthus* species for alleviating human dietary deficiencies. **South African Journal of Botany**, Johannesburg, v. 115, p. 65–73, 2018.

KANENSI, O. J.; OCHOLA, S., GIKONYO, N. K.; MAKOKHA, A. Optimization of the period of steeping and germination for Amaranth grain. **Journal of Agriculture and Food Technology**, Cairo, v. 1, p. 101–105, 2011.

KAUFFMAN, C. S. The status of grain amaranth for the 1990s. **Food Reviews International**, London, v. 8, n. 1, p. 165–185, 1992.

KAUFFMAN, C. S.; HASS, P. W. Grain amaranth: A crop with low water requirements and high nutritional value. In: W. Lockeretz. (org. **Environmentally Sound Agriculture.** Praeger Publishers, New York, p. 299-313, 1983.

KAUFFMAN, C.S.; WEBER, L.E. Grain amaranth. In: JANICK, J.; SIMON, J.E. (Org.), **Advances in New Crops**. Timber Press, Portland, OR, p. 127-139, 1990.

KAUL, H.-P.; KRUSE, M.; AUFHAMMER, W. Yield and radiation use efficiency of pseudocereals compared with oats. **Pflanzenbauwissenschaften**, [*s.l.*], v. 4, p. 9–14, 2000.

KEHINDE, T. O.; AJALA, M. O.; DANIEL, I. O.; OYELAKIN, O. O. Physiological and genetic integrity of amaranth (*Amaranthus* spp.) seeds during storage. **International Journal of Plant Breeding and Genetics**, Dubai, v. 7, p. 35-46, 2013.

KIETLINSKI, K. D.; JIMENEZ, F.; JELLEN, E. N.; MAUGHAN, P. J.; SMITH, S. M.; PRATT, D. B. Relationships between the weedy *Amaranthus hybridus* (Amaranthaceae) and the grain amaranths. **Crop Science**, Madison, v. 54, n. 1, p. 220-228, 2014.

KOCHAR, S. L. **Tropical Crops**: a textbook of economic botany. MacMillan. 1986. 467p.

KOOYENGA, D. K.; GELLER, M.; WATKINS, T. R.; GAPOR, A.; DIAKOUMAKIS, E.; BIERENBAUM, M. L. **Antioxidant effects of tocotrienols in patients with hyperlipidemia and carotid stenosis**. PORIM International Palm Oil Congress, September 23-28; p 152-160. Kuala Lumpur, Malaysia. Nutrition Conference. 1996.

KRAUJALIS, P.; VENSKUTONIS, P. R. Supercritical carbon dioxide extraction of squalene and tocopherols from amaranth and assessment of extracts antioxidant activity. **The Journal of Supercritical Fluids**, Virginia, v. 80, p. 78–85, 2013.

LASCO, R. D.; DELFINO, R. J. P.; ESPALDON, M. L.O. **Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change**. Wiley Interdisciplinary Reviews: Climate Change, 2014.

LE BISSONNAIS, Y. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. **European Journal of Soil Science**, London, v. 47, n. 4, p. 425-437, 1996.

LEE, J. H.; AUFHAMMER, W.; KÜBLER, E. Gebildete, geerntete und verwertbare Kornerträge der Pseudocerealien Buchweizen (*Fagopyrum esculentum* Moench), Reismelde (*Chenopodium quinoa* Willd.) und Amarant (*Amaranthus hypochondriacus* L. x *A. hybridus* L.) in Abh¨angigkeit von pflanzenbaulichen Maßnahmen. **Die Bodenkultur**, Warsaw, v. 47, n.1, p. 5–14, 1996.

LIPPI, G.; TARGHER, G.; FRANCHINI, M. Vaccination, squalene and antibodies: facts and fiction? **European Journal of Internal Medicine**, [*s.l.*] v. 21, n. 2, p. 70-73, 2010.

MALLIGAWAD, L. H.; PATIL, V. C. Effect of plant density and planting geometry on growth and yield of grain amaranths. **Karnataka Journal of Agricultural Sciences**, Rome, v. 14, p. 11-17, 2001.

MARCÍLIO, R.; AMAYA-FARFAN, J.; SILVA, M. A. A. P. Fracionamento do grão de amaranto (*A. cruentus*) brasileiro e suas características composicionais. **Ciência e tecnologia de alimentos**, São Paulo, v. 23, n. 3, p. 511-516, 2003.

MARTINEZ-LOPEZ, A.; MILLAN-LINARES, M. C.; RODRIGUEZ-MARTIN, N. M.; MILLAN, F.; DE LA PAZ, S. M. Nutraceutical value of kiwicha (*Amaranthus caudatus* L.), **Journal of Functional Foods**, Amsterdam, v. 65, p. 5-12, 2020.

MAYES, S. The potential for underutilized crops to improve security of food production. **Journal of experimental botany**, Oxford, v. 63, n. 3, p. 1075-1079, 2012.

MAZZINI, J. M. Atole de amaranto y su efecto potencial sobre la composición corporal de adultas mayores. **Nutrición clínica y dietética hospitalaria**, Madrid, v. 38, n. 2, p. 14-19, 2019.

MLAKAR, S. G.; TURINEK, M.; JAKOP, M.; BAVEC, M.; BAVEC, F. Grain amaranth as an alternative and perspective crop in temperate climate. **Journal of Geography**, London, v. 5, p. 135–145, 2010.

MONTEIRO, M. A.; MARTINS, A. B. N.; COSTA, C. J.; AUMONDE, T. Z.; VILLELA, F. A.; PEDÓ, T. Crescimento inicial de plantas de *Amaranthus cruentus* L. cv. BRS alegria submetidas ao alagamento do solo. **Revista Cultivando o Saber**, Cascavel, v. 9, n. 4, p. 124-131, 2016.

MORALES, E.; LEMBCKE, J.; GRAHAM, G. G. Nutritional Value for Young Children of Grain Amaranth, and Maize-Amaranth mixtures: Effect of Processing. **Journal of Nutrition**, Oxford, v. 118, n. 1, p. 78-85. 1988.

MORTON, J. F. The impact of climate change on smallholder and subsistence agriculture. **Proceedings of the National Academy of Sciences of the United States of America,** v. 104, p. 19680–19685, 2007.

MUYONGA, J. H.; ANDABATI, B.; SSEPUYA, G. Effects of heat processing on selected grain amaranth physico-chemical properties. **Food Science and Nutrition**, [*s.l.*], v. 2, n. 1, p. 9-16, 2014.

MYERS, R. L. Amaranth: New Crop Opportunity. In: JANICK, J.; SIOMN, J.E. (Org.), **Progress in New Crops**. ASHS Press, Alexandria, VA. p. 207-220 1996.

NATIONAL RESEARCH COUNCIL (NRC). **Amaranth**: modern prospects for an ancient crop. Washington: National Academy Press, 1984. 77p.

NAWIRI, M. P.; NYAMBAKA, H.; MURUNGI, J. I. Sun-dried cowpeas and amaranth leaves recipe improves β-carotene and retinol levels in serum and hemoglobin concentration among preschool children. **European Journal of Nutrition**, Munich, v. 52, p. 583–589, 2013.

O'BRIEN, G. K.; PRICE, M. L. **Amaranth Grain and Vegetable Types.** ECHO Technical Note. ECHO, North Fort Myers, FL 33917, USA, 2008. 15p. Disponível em: https://www.researchgate.net/publication/290430499_Amaranth_Seed_Rate_and_Biological_Efficiency_of_Maize-Leaf_Amaranth_Intercropping_Systems [Acesso em: 27 nov. 2020].

OLIVEIRA FILHO, A. F.; SILVA, M. N. C.; INNECCO, R.; BEZERRA, F. T. C.; ABREU, W. E. Efeito do arranjo de plantio da quinoa em baixa altitude. **Revista de Ciências Agrárias**, Lisbon, v. 41, n. 2, p. 367–375, 2018.

OLOFINTOYE, J. A. T.; ABAYOMI, Y. A.; OLUGBEMI, O. Yield responses of grain amaranth (*Amaranthus cruentus* L.) varieties to varying planting density and soil amendment. **African Journal of Agricultural Research**, [*s.l.*] v. 10, n. 21, p. 2218-2225, 2015.

PEIRETTI, E. G.; GESUMARIA, J. J. Influencia de la distanzia entre lineas sobre el crecimiento y rendimento de amaranto granifero (*Amaranthus* spp.). **Investigacion Agraria: Produccion y Proteccion Vegetales**, La Rioja, v. 13, n. 1–2, p. 139–151, 1998.

PETER, K.; GANDHI, P. Rediscovering the therapeutic potential of *Amaranthus* species: a review. **Egyptian Journal of Basic and Applied Sciences**, London, v. 4, p. 196–205, 2017.

PETR, J.; MICHALIK, I.; TLASKALOVA, H.; CAPOUCHOVA, I.; FAMERA, O.; URMISKA, D.; TUKOVA, L.; KNOBLOCHOVA, H. Extension of the spectra of plant products for the diet in celiac disease. **Czech Journal of Food Sciences**, Prague, v. 21, p. 59-70, 2003.

PISARIKOVA, B.; PETERKA, J.; TRCKOVA, M.; MOUDRY, J.; ZRALY, Z.; HERZIG I. The content of insoluble fibre and crude protein value of the aboveground biomass of *Amaranthus cruentus* and *A. hypochondriacus*. **Czech Journal of Animal Science**, Prague, v. 52, p. 348-353, 2007.

PITTELKOW, F.; BIANCHINI, A.; PEREIRA, P. S.; BELUFI, L. M.; DE ASSIS BIANCHINI. M.; ROSA, R. Evaluation of Agronomic Performance of Amaranthus (*Amaranthus cruentus* cv. BRS Alegria) in Times and Seed Densities. **Journal of Experimental Agriculture International,** Cambridge, v. 38, n. 6, p. 1-13, 2019.

POSPIŠIL, A.; POSPIŠIL, M.; POLJAK, M.; JUKIĆ, Ž. Influence of nitrogen fertilization on the chemical composition of amaranth (*Amaranthus* spp.) seed. **Cereal Research Communications**, Budapest, v. 36, p. 1227-1230, 2008.

POSPISIL, A.; POSPISIL, M.; VARGA, B.; SVECNJAK, Z. Grain yield and protein concentration of two amaranth species (*Amaranthus* spp.) as influenced by the nitrogen fertilization. **European Journal of Agronomy**, Amsterdam, v. 25, p. 250–253, 2006.

RASCHKE, V.; B. CHEEMA. Colonization, the New World Order, and the eradication of traditional food habits in East Africa: historical perspective on the nutrition transition. **Public Health and Nutrition**, Cambridge, v. 11, p. 662–674, 2008.

RASTOGI, A.; SHUKLA, S. Amaranth: a new millennium crop of nutraceutical values. **Critical Reviews in Food Science and Nutrition**, London, v. 53, n. 2, p. 109–125, 2013.

RICHARDS. L.A. (Ed.). **Diagnóstico y rehabilitacion de suelos salinos y sodicos.** 5. ed. México: Centro Regional de Ayuda Técnica, 1970. 172p.

RODRIGUES, D. B.; ROSA, T. D. A.; GULARTE, J. A.; DE MEDEIROS, D. C.; DE TUNES, L. M. Profundidade de semeadura no desenvolvimento inicial de pseudocereais. **Revista Verde de Agroecologia e Desenvolvimento Sustentável**, Pombal, v. 11, n. 3, p. 182-186, 2016.

SANTOS, M. A.; BIANCHINI, A.; PEREIRA, P. S. X.; DAROS, R. F.; DEUS, M. S.; SILVA, V. S. M.; GURKA, C. A. Q.; COSTA, P. M. C. Comparison between planting and sowing as forms of Amaranthus (*Amaranthus* spp.) propagation and investigation of different seeding depths. **Journal of Experimental Agriculture International**, Amsterdam, v. 38, n. 1, p. 1-6, 2019.

SANZ-PENELLA, J. M.; WRONKOWSKA, M.; SORAL-SMIETANA, M.; HAROS, M. Effect of whole amaranth flour on bread properties and nutritive value. **Food Science and Technology**, [*s.l.*], v. 50, p. 679–685, 2013.

SAUNDERS, R. M.; BECKER, R. Amaranthus: a potential food and feed source In: POMERANZ, Y. (Org.). **Advances in Cereal Science and Technology**, American Association of Cereal Chemistry, St Paul, MN, v 6. p. 357-396, 1984.

SCHMIDT, K. M. Chapter 4 - Lipid metabolism in plants, In: NEALE, D.R.; MCLEOD, R.S. (Org.) **Biochemistry of Lipids, Lipoproteins and Membranes** (Seventh Edition), Elsevier, p. 121-159, 2021.

SCHMIDT, M.; LAM, N. T.; HOANH, M. T.; PADULOSI, S. Promoting neglected and underutilized tuberous plant species in Vietnam. In: HAAS, R.; CANAVARI, M.; SLEE, B.; TONG, C.; ANURUGSA, B. (Org.) **Looking East Looking West**: Organic and Quality Food Marketing in Asia and Europe. Wageningen Academic Publishers, The Netherlands, p. 183-193, 2010.

SHRIEF, S.A.; SHABANA, R.; IBRAHIM, A.F.; GEISLER, G. Variation in seed yield and quality characters of four spring oil rapeseed cultivars as influenced by population arrangements and densities. **Journal of Agronomy and Crop Science**, London, v. 165, p. 103–109, 1990.

SILVA, J.; BIANCHINI, A.; COSTA, P.; LOBO, F.; ALMEIDA, J. P.; DE MORAES, M. Amaranth Response to Water Stress. **Journal of Experimental Agriculture International**, Amsterdam, v. 40, n. 1, p. 1-9, 2019.

SILVA-SANCHEZ, C.; BARBA DE LA ROSA, A. P.; LEÓN-GALVÁN, M. F., DE LUMEN, B. O., DE LEÓN-RODRÍGUEZ, A.; GONZALEZ DE MEJÍA, E. Bioactive peptides in amaranth (*Amarathus hypochondriacus*) seed**. Journal of Agricultural and Food Chemistry**, Washington, v. 56, n. 12, p. 33–40, 2008.

SINGH, B. P.; WHITEHEAD, W. F. **Management methods for producing vegetable amaranth**. In: Janick, J. (ed.), Progress in new crops. ASHS Press, Arlington, VA, p. 511-515. 1996.

SINGHAL, R. S.; KULKARNI, P. R. Review: Amaranths an Underutilized Resource. **International Journal of Food Science and Technology**, London, v. 23, p. 125-139, 1988.

SPEHAR, C. R. Amaranto BRS Alegria – Alternativa para diversificar os sistemas de produção. **Pesquisa Agropecuaria Brasileira**, Brasília, v. 39, n. 1, p. 85-91, 2003.

SPEHAR, C. R. **Amaranto**: opção para diversificar a agricultura e os alimentos. Planaltina - DF: Embrapa Cerrados, 2007. 136 p.

SPEHAR, C. R.; TEIXEIRA, D.L. **Amaranto**: Alternativa na cobertura do solo e na produção de grãos. Embrapa - Guia técnico do produtor rural, Ano IV, n. 35, 1999. 2p.

SPEHAR, C. R.; TEIXEIRA, D.L.; LARA, W. Amaranth BRS Alegria: alternative for diversification of cropping systems. **Pesquisa Agropecuária Brasileira**, Brasília, v. 38, p. 659-663, 2003.

STALLKNECHT, G. F.; SCHULZ-SCHAEFFER, J. R. Amaranth rediscovered. In: JANICK J.; SIMON, J.E. (Org.). **New Crops**. Wiley, New York, p. 211-218, 1993.

STETTER, M. G.; MÜLLER, T.; SCHMID. K. Incomplete domestication of South American grain amaranth (*Amaranthus caudatus*) from its wild relatives. **Biorxiv**, [*s.l.*] v. 26, n. 3, p. 871-876, 2015.

STETTER, M. G.; SCHMID, K. J. Analysis of phylogenetic relationships and genome size evolution of the Amaranthus genus using GBS indicates the ancestors of an ancient crop. **Molecular Phylogenetics and Evolution**, New York, v. 109, p. 80–92, 2017.

STORDAHL, J. L.; SHEAFFER, C. C.; DICOSTANZO, A. Variety and maturity affect amaranth forage yield and quality. **Journal of Production Agriculture**, Madison, v. 12, p. 249-253, 1999.

SUNIL, M., HARIHARAN, A. K., NAYAK, S., GUPTA, S., NAMBISAN, S. R., GUPTA, R. P. The draft genome and transcriptome of Amaranthus hypochondriacus: a C4 dicot producing high-lysine edible pseudo-cereal. **DNA Research**, Oxford, v. 21, n. 6, p. 585-602, 2014.

TAIZ, L.; ZEIGER, E. **Fisiologia vegetal**. 6. ed. Porto Alegre: Artmed, 2017. 888 p.

TAUB, D. R.; JEFFREY, R. S.; JAMES, S.C. Growth in elevated CO_2 protects photosynthesis against high-temperature damage. **Plant, Cell and Environment**, [*s.l.*], v. 23, p. 649–656, 2000.

TEIXEIRA, D. L.; SPEHAR, C.R.; SOUZA, L.A.C. Caracterização agronômica de amaranto para cultivo na entressafra no Cerrado. **Pesquisa Agropecuária Brasileira**, Brasília, v. 38, n. 1, p. 45-51, 2003.

TIWARI, A.; SONI, V.; LONDHE, V. An overview on potent indigenous herbs for urinary tract infirmity: urolithiasis. **Asian Journal of Pharmaceutical and Clinical Research**, Patiala, v. 5, n. 1, p. 7-12, 2012.

UFOEGBUNE, G.; ERUOLA, K. O. Performance of *Amaranthus* species under two different environmental conditions in derived savannah agroecology, Southwestern Nigeria. **African Journal of Agriculture and Technological Environment**, Nigeria, v. 4, p. 33-45, 2016.

UNITED STATES DEPARTMENT OF AGRICULTURE (USDA). **Subset, Food, and All Foods.** National Nutrient Database for Standard Reference, Amaranth grain**.** v. 28, 2016
UNITED STATES DEPARTMENT OF AGRICULTURE, AGRICULTURAL RESEARCH SERVICE AND NATURAL RESOURCES CONSERVATION SERVICE (USDA). **Soil quality**

indicators: pH. 1998. Disponível em: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_052208.pdf Acesso em: 25 out. 2022

VÉLEZ-JIMENEZ, E.; TENBERGEN, K.; SANTIAGO, P.; CARDADOR-MARTÍNEZ, M. A. Functional attributes of Amaranth. **Austin Journal of Nutrition and Food Sciences**, Austin, v. 2, p. 1, p. 1-6, 2014.

VENSKUTONIS, P. R.; KRAUJALIS, P. Nutritional components of amaranth seeds and vegetables: a review on composition, properties, and uses. **Comprehensive Reviews in Food Science and Food Safety**, Chicago, v. 12, n.4, p. 381-412, 2013.

WATKINS, T.; LENZ, P.; GAPOR, A.; STRUCK, M.; TOMEO, A.; BIERENBAUM, M. Gammatocotrienol as a hypocholesterolemic and antioxidant agent in rats fed atherogenic diets. **Lipids**, Urbana, v. 28, p. 1113-1118, 1993.

WEBB, D. M.; SMITH, D. W.; SHULZ-SCHAEFFER, J. Amaranth seedling emergence as affected by seeding depth and temperature on a thermogradient plate. **Agronomy Journal**, Madison, 79, 23–26, 1987.

WEBER, L. E.; APPLEGATE, W. W.; JOHNSON, D. L.; NELSON, L. A.; PUTNAM, D. H.; LEHMAN, J. W. **Amaranth Grain Production Guide**. Rodale Press, Emmaus, PA, 1989.

WELLBURN, A. R. The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. **Journal of Plant Physiology**, Amsterdam, v. 144, n. 2, p. 307-313, 1994.

WILLIAMS, J. T.; BRENNER, D. Grain amaranth (*Amaranthus* sp.). In: WILLIAMS, J.T. (Org.), **Cereals and Pseudocereals**. Chapman & Hall, London, p. 129–186, 1995.

ŽAJOVÁ, A.; KOŠTÁL, L.; VEREŠČÁK, M. An unconventional crop – Amaranth (Amaranthus). In: Magdaléna Lacko-Bartošová (Org.) **Acta fytotechnica et zootechnica**, Proceedings of the International Scientific Conference on the Occasion of the 55th Anniversary of the Slovak Agricultural University of Nitra, 4, 216-217., Special issue, 2001.

ZUBILLAGA, M. F.; CAMINA, R.; ORIOLI, G. A.; FAILLA, M.; BARRIO, D. A. Amaranth in southernmost latitudes: plant density under irrigation in Patagonia, Argentina. **Revista Ceres**, Viçosa, v. 67, p. 2, 93-99, 2020.