agriculture

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Comparison of Agronomic Parameters and Nutritional Composition on Red and Green Amaranth Species Grown in Open Field Versus Greenhouse Environment

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Abstract: Previously, researchers have not paid attention to indigenous African leafy vegetables such as nightshade and kale, however, amaranth species have recently gained popularity due to their adaptability to various climatic conditions and their cultivation in both open fields and hydroponics. Amaranth species are ranked among the underutilized leafy vegetables with medicinal properties, economic values, nutritional and health benefits. This study aimed to compare the growth parameters and nutritional composition of two consumed red (*Amaranthus Cruentus* L.) and green (*Amaranthus Graecizans* L.) amaranth species in South Africa, cultivated in an open field versus a greenhouse. The findings showed a high chlorophyll content and large leaf area under open field conditions on red and green species. The number of leaves and stem height were higher in the greenhouse cultivation system. In open field cultivation, minerals such as calcium, magnesium, phosphorus, iron, zinc, aluminium, copper and manganese for both species were significantly higher whilst potassium, sodium, boron, sulphur were significantly higher in the greenhouse production. The sufficient total nitrogen and ash were recorded in the open field production, and no significant difference was observed between the open field and greenhouse on moisture and ash content of *A. Cruentus*. In conclusion, *A. Cruentus* and *A. Graecizansn* grown in an open field had higher proximate and mineral composition over the greenhouse cultivation system.

Keywords: food security; growing conditions; leafy vegetables; minerals elements; proximate composition; underutilized vegetables

Citation: Managa, G.M.; Nemadodzi, L.E. Comparison of Agronomic Parameters and Nutritional Composition on Red and Green Amaranth Species Grown in Open Field Versus Greenhouse Environment. *Agriculture* **2023**, *13*, 685. https://doi.org/10.3390/agriculture13030685

Academic Editor: Vitalii Nitsenko

Received: 27 February 2023
Revised: 5 March 2023
Accepted: 13 March 2023
Published: 15 March 2023

1. Introduction

Amaranthus, known as amaranth, is a short-lived annual, dicotyledonous and herbaceous plant, widely distributed throughout the world, which belongs to the Amaranthacea family [1,2]. According to [3], Amaranthacea comprises 65 genera and 900 species, the majority being native to Africans, found in tropical and subtropical regions, and Central and South America. However, most are considered cosmopolitan in distribution and are often introduced to a particular region or place [4]. Amaranth can further be distinguished by two morphological types, described as red and green morphs amaranth [2]. It is one of the underutilized, yet important multipurpose plants previously known as a weed. Although some species are still considered weeds, it has become popular and exploited all over the world as a grain or leafy vegetable for food, forage for animals and as an ornamental [5,6].

Over the years, the *A. cruentus* species was described as a grain amaranth whilst *A. greazicans* was reported as a weed's amaranth species [7]. To date, *A. cruentus* and *A. greazicans* are the most common species produced for leafy vegetables [8] and according to [9] they are among the commonly used and consumed edible species of amaranth in South Africa.

In South Africa, amaranth is commonly known as "vowa" by the VhaVenda tribe, "theepe" by the BaPedi tribe, "cheke" by the VaTsonga tribe and pigweed/cockscomb and/or hell's curse in English [10]. Utilization of amaranth is reported in many parts of Limpopo, followed by KwaZulu-Natal, and the North–West and Mpumalanga provinces [11] of South Africa. According to [12], the young, fresh and succulent leaves of amaranth are handpicked weekly in the summer after the first rains, mostly by older women. In Africa, amaranth is considered an indigenous vegetable that is cooked on its own or in combination with other leafy vegetables and is consumed with other stable foods such as porridge [13]. For instance, the VhaVenda tribe cooks *Amaranthus* with pumpkin leaves (*Cucurbita pepo* L.), jew mallow/Bush okra (*Corchorus olitorius*), nightshade (*Solanum nigrum* L.) and blackjack (*Quercus marilandica*). Cooked leaves may also be dried in the shade or refrigerated and stored for consumption during off seasons [14] in winter and/or in drought periods.

Amaranth leaves are reported to have a low content of saturated fats and an absence of cholesterol, therefore, they can be considered as an alternative source of protein in a human diet in comparison with animal protein [15] that is 13–18% higher when compared with wheat (14%) and cereals such as corn (10.3%) [6]. In addition, amaranth leaves are reported to contain dietary minerals such as Ca, K, Cu, Mg, P, Mg, Fe and Zn [16–18] including vitamins such as β-catotene, vitamin B6, vitamin C, riboflavin and folate [19–21]. Ref. [22] reported that the consumption of amaranth leaves is vital, since one cup of cooked, boiled and drained amaranth leaves contains 90% vitamin C, 73% vitamin A, 28% calcium and 28% iron of the daily nutrient requirement.

Food insecurity and hunger remains to be a global challenge, with many countries still food insecure or vulnerable to food insecurity [23]. Hence, the 2030 Agenda for Sustainable Development and the United Nations Decade of Action on Nutrition (2016–2025) both call on all countries and stakeholders to collaborate to combat hunger and prevent malnutrition in different forms by 2030 [24]. Despite being classified as food secure at the national level, according to [25] approximately 16 million people in South Africa are food insecure, with the majority living in rural areas, and this trend has been constant in recent years [18]. Due to nutrient deficiencies such as vitamin A, iron, zinc and vitamin C [26], the current focus is on indigenous and traditional food crops and their positive impact on the sustainability of our food and agricultural systems as measures to address food insecurity [27]. Amaranth is one of these traditional food crops identified for its exceptional nutritional value and widespread benefits as a sustainable food source, implying that its inclusion in daily diets can help increase the household food supply and improve household food security [28].

Amaranthus is a C_4 fast-growing plant [29] with a low production cost that makes it one of the cheapest green leafy vegetables in the tropical market, often referred to as the poor man's vegetable [30]. Amaranths have a high capacity of osmotic adjustment [6] and a C_4 photosynthetic pathway that allows efficient use of CO_2 in a large range of temperature and moisture stress environments, which is considered a major factor in their wide geographical distribution. In addition, [31] and [32] indicated that various species can grow under varied soil, optimally in warm conditions and are tolerant to drought, plant diseases and adverse climatic conditions [20]. However, [9] reported that in South Africa and other African countries, amaranth is hardly cultivated because people believe that leafy vegetables grow naturally and can be collected in the fields and/or in the household backyards.

In the past years, due to the lack of formal certified seed suppliers of amaranth, in the Bushbuckridge area of the Limpopo and Mpumalanga provinces where it is commonly consumed, women normally harvest and store amaranth seed, which they later broadcast in their fields when a decline in the population is observed [9].

In the recent years, an interesting approach has developed of using greenhouses as a strategy to produce high-potential crops such as amaranth throughout the year, in different soil types and under different agroclimatic conditions with a minimal management of production inputs [6,19]. Ref. [33] indicated that should appropriate measures be taken, greenhouses have the potential to increase agricultural production by accelerating crop development and increasing the biomass per unit of cultivated area when compared to open field conditions. Furthermore, greenhouses allow crops to develop with little risk to production, protecting plants in contrast to open field crops, which are more vulnerable to environmental changes and rely on natural factors [6]. Various factors such as environmental stress can affect the chemical composition of amaranth, thus stimulating the production of antioxidant compounds [34]. The cultivation of the amaranth plant does not extensively vary in South Africa, the main reason for cultivation being for household food security and replenishment of the seed bank [35]. It is crucial to find ways to increase productivity by growing *Amaranthus* species in the hydroponics and to monitor other important aspects such as the chemical composition of the harvested amaranth leaves. Therefore, the potential to advance the production and consumption of amaranth is fundamental. This study aimed to compare the agronomical parameters and nutritional composition of two different commonly consumed amaranth species (*Amaranthus Cruentus* L.) and (*Amaranthus Graecizans* L.) in South Africa cultivated in an open field vs. a greenhouse. The hypothesis of the study was that different cropping system will have no impact on the physiology and the nutritional composition of the red and green *Amaranthus* species.

2. Materials and Methods

2.1. Study Sites

Location and cropping systems:

Greenhouse: The pot experiment was conducted in the greenhouse with a minimum and maximum air temperature range of 7.4 to 44.9 °C. It was situated at the University of South Africa, Florida Science Campus, Rooderpoot (Latitude: −26°9′29.274″; Longitude: 27°55′17.663″). The average relative humidity inside the greenhouse was 68% [36] during the planting period (October 2021 to February 2022). The plastic pots (18 cm diameter, 14.5 cm height and 18 cm width) were used for growing the seeds. Open field: The experiment was conducted in Itsani village, located about 6 km southwest of Thohoyandou, in the Thulamela Local Municipality of the Vhembe District (Latitude: −22.94786, Longitude: 30.47276) situated in the Limpopo Province of South Africa. During the summer planting period, the temperatures ranged from 26–32 °C with an average rain fall of ±500 mm annually, mostly experienced during the summer months of October to March. The production cycle was about 4 months during the summer seasons of October 2021 to December 2021 for both cropping systems.

2.1.1. Treatments

The two Amaranth species *Amaranthus Cruentus* L. and *Amaranthus Graecizans* L. used in this study were obtained from a local reputable seeds' supplier. For each cropping system, greenhouse and open field planting was conducted through direct sowing in a sandy loam soil. Pots were arranged at 0.3 m (inter) × 0.25 m (intra) spacing on the greenhouse benches as prescribed by [37] with a crop density established at 30 plants per m^2 per accession, totalling to 60 pot plants. In this study, cultivation was done without the application of fertilizers as prescribed by [9]. In both cultivation systems, irrigation was done every second day after sowing and was stopped a week before harvest.

2.1.2. Sample Preparation

Healthy edible leaves of the two Amaranth species *A. Cruentus* and *A. Graecizans* from each cropping system were randomly harvested at the 8-leaf stage reached 60–95 days after planting as prescribed by [38,39]. The harvested leaves from the open field cropping system were transported on the same day, by placing them inside a cooler box with ice packs to prevent degeneration of quality (wilting, yellowing and spoilage) to the University of South Africa laboratory, Science Campus, Florida. Leaves from each cropping system were removed from the stems, washed thoroughly with tap water to remove any soil debris and air-dried (30 ± 2) on absorbent paper towel at room temperature for 4 days until sufficiently crisped, as prescribed by [40]. Dried leaves from each cropping system were grounded into fine powder using a Russel Hobbs Blender (500W, Shanghai, China), Zhongshan Jast

Electrical Appliance, Co., Ltd. in order to produce a homogeneous powder, and powdered samples were used for the nutritional analysis.

2.2. Procedures

2.2.1. Agronomic Parameters

To determine the agronomic parameters, 25 plants per amaranth species from each cropping system were randomly sampled. The total number of green-emerged leaves was counted for each of the randomly selected plants to record the total number of leaves per plant. The plant height was manually measured in centimetres (cm) using a measuring tape, with an accuracy of 0.01 mm placed vertically on the substrate surface and the measurement was taken at the apical meristem. The length and width of leaves were measured with a tape measure to calculate the leaf area using a liner equation as prescribed by [3] using the formula below:

$$\text{Leaf area (cm}^2\text{)} = 0.654 \times (\text{L} \times \text{W})$$

where: 0.654 = leaf shape coefficient; L = length of leaf (cm); W = width of leaf (cm) measured at half length.

In addition, leaf chlorophyll content on the middle leaves found between the bottom and top leaves of 20 plants was measured and replicated three times using a non-destructive method with a Spad 502 chlorophyll meter, KONIKA MINOLTA, Japan.

2.2.2. Chemical Analysis

The nutritional traits of leaves were determined by chemical analysis which included the total nitrogen, moisture, ash and minerals from all the samples. The total nitrogen was determined by the dry combustion method using a Carlo Erba NA 1500 C/N/S Analyser (Carlo Erba NA, Stanford, CA, USA) as described by [41,42]. Moisture and ash were carried out according to the standardized methods of [43], where the ash content was determined by the incineration of a dried powdered sample in a muffle furnace (Zhengzhou Protech Technology Co., Zhengzhou, China) at 550 °C for 12 h until the ash turned white. Moisture was determined by drying in a forced-air drying oven (air re-circulating oven, Carbolite, UK) (934.01) at 105 ± 1 °C for 4 h. Mineral elements comprising calcium, potassium, magnesium, sodium, phosphorus, iron, zinc, aluminium, boron, copper, manganese and sulphur concentrations were determined according to the method by the Association of Official Agricultural Chemists [43] after a cooling period. This process involved inductively coupled plasma spectroscopy and the results of the nutritional analysis were reported on a dry weight basis.

2.3. Statistical Analysis

Data were subjected to a one-way analysis of variance (ANOVA) performed with Genstat 64-bit Release 20.1 (PC/Windows 8–10) software. Where significance differences were observed, means separation was conducted by an LSD test at a 5% significance level.

3. Results

3.1. Agronomic Parameters

Amaranthus Graecizans cultivated in open field conditions had the highest leaf chlorophyll content of 67.9 nm and b leaf area of 4591 cm^2. On the contrary, amaranth grown in the greenhouse exhibited a lower chlorophyll content and leaf area of 43.3 nm and 1317 cm^2, respectively. Notably, *A. Graecizans* cultivated in the greenhouse had a significant number of leaves per plant (39.33) and showed a faster and more robust development with taller and thicker stems (70.80 cm) when compared to open field grown plants which had 23.00 leaves and a 59. 00 stem height, respectively. The variation in agronomic parameters between the red and green *Amaranthus* species grown in two cultivation systems including the analysis of variance (ANOVA) of leaf chlorophyll content, leaf area, number of leaves and stem height showed a significant difference ($p \leq 0.01$) between the two-cropping environment: open field vs. greenhouse conditions as shown in Table 1 below, and Figure 1 respectively.

Table 1. Comparison of agronomic parameters of *A. Graecizans* L. grown in open field vs. greenhouse.

	Relative Chlorophyll Content (nm) (3× Replications)	Leaf Area (cm^2)	Number of Leaves	Stem Height (cm)
Treatments				
Open field	67.9 ^{a}	4591 ^{a}	23.00 ^{b}	59.00 ^{b}
Greenhouse	43.3 ^{b}	1317 ^{b}	39.33 ^{a}	70.80 ^{a}
rep	3	3	3	3
d.f.	4	4	4	4
SEM	1.92	154.2	0.624	0.363
SED	2.72	218.0	0.882	0.513
LSD (5%)	7.55	605.4	2.449	1.425
F probability	≤0.001	≤0.001	≤0.001	≤0.001

SEM is the standard error of means, SED is the standard error of difference, LSD is the *t*-test least significant difference. SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

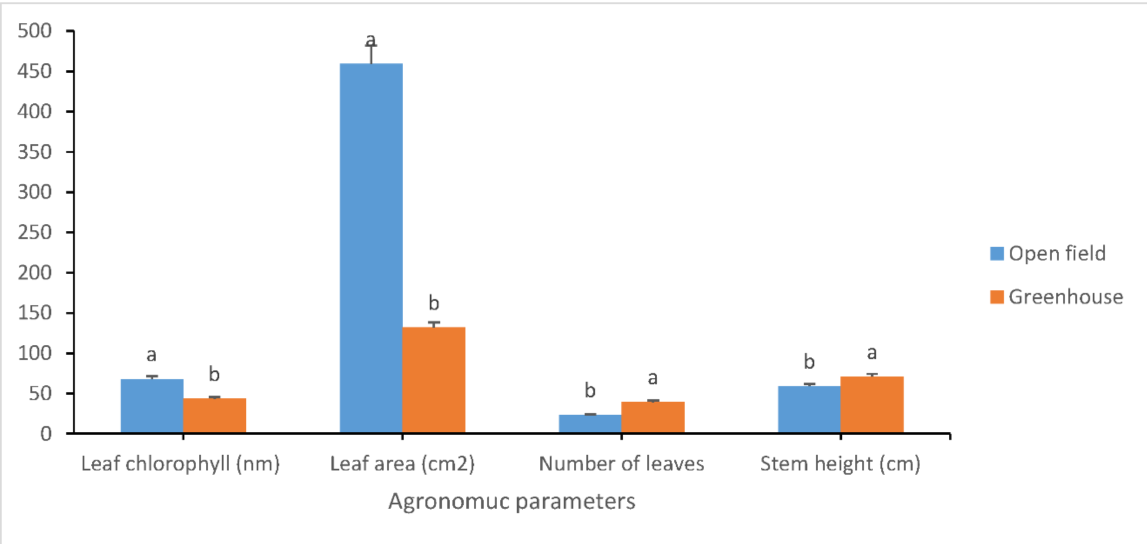

Figure 1. A comparative diagram showing the differences in growth parameters of *A. Graecizans* L. under open field (Blue) versus greenhouse (Orange) conditions, a referrer to open field whilst b referrers to greenhouse.

The findings presented in Table 2 show that *A. Cruentus* in open field cultivation had a significantly higher leaf chlorophyll content of (46.37 nm) whilst the least leaf chlorophyll content of (27.27 nm) was recorded from *A. Cruentus* grown in the greenhouse. The analysis of variance of leaf area, number of leaves and stem height did not show a significant difference ($p \leq 0.01$) between the open field and greenhouse-grown *A. Cruentus* (* see Table 2 and Figure 2).

3.2. Proximate Composition

Table 3 outlines the proximate composition of *A. Graecizans* grown in the open field vs. greenhouse, where there was a significant difference ($p \leq 0.01$) amongst the two cultivation environments. *A. Graecizans* grown in the open field exhibited the highest total nitrogen (5.50), moisture content (6.26) and ash content (18.40), whilst *A. Graecizans* cultivated in the greenhouse had the least proximate composition content (* see Table 3 and Figure 3). On the contrary, A. *Cruentus* had the highest content of total nitrogen (5.23) detected in the open field. However, the amount of moisture and ash content in this accession was not significantly different ($p \leq 0.01$) amongst the two cropping systems as shown in Table 4 and Figure 4.

Table 2. Comparison of agronomic parameters *A. Cruentus* L. in the open field vs. greenhouse.

	Relative Chlorophyll Content (3× Replications) (nm)	Leaf Area (cm^2)	Number of Leaves	Stem Height (cm)
Treatments				
Open field	46.37 ^{a}	7622 ^{a}	16.33 ^{a}	84.8 ^{ab}
Greenhouse	27.27 ^{b}	5394 ^{ab}	27.33 ^{ab}	106.3 ^{a}
rep	3	3	3	3
d.f.	4	4	4	4
SEM	1.100	788.6	1.202	2.56
SED	1.555	1115.2	1.700	3.63
LSD (5%)	4.318	3096.2	4.719	10.07
F probability	<0.001	0.116	0.003	0.004

SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

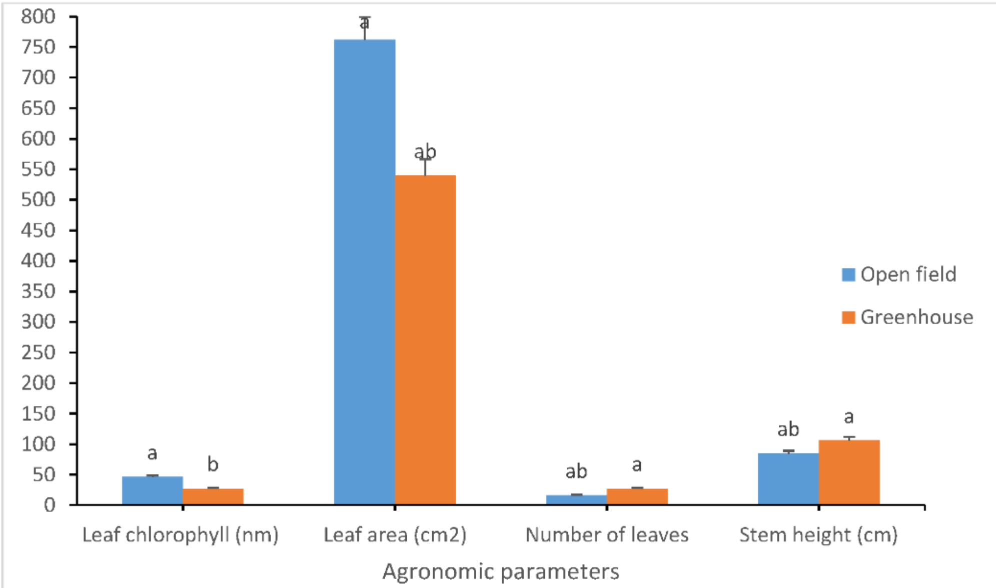

Figure 2. A comparative diagram showing the differences in growth parameter of *A. Cruentus* L. under open field (Blue) versus greenhouse (Orange) a referrer to open field whilst b referrers to greenhouse.

Table 3. Proximate composition of amaranth leaves from *A. Graecizans* L. in the open field vs. greenhouse on a dry weight basis (%).

	Total Nitrogen	Moisture	Ash
Treatments			
Open field	5.50 ^{a}	6.26 ^{a}	18.40 ^{a}
Greenhouse	3.63 ^{b}	5.57 ^{a}	14.27 ^{b}
rep	3	3	3
d.f.	4	4	4
SEM	0.0621	0.0751	0.143
SED	0.0878	0.1062	0.203
LSD (5%)	0.2438	0.2950	0.563
F probability	<0.001	0.003	<0.001

SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

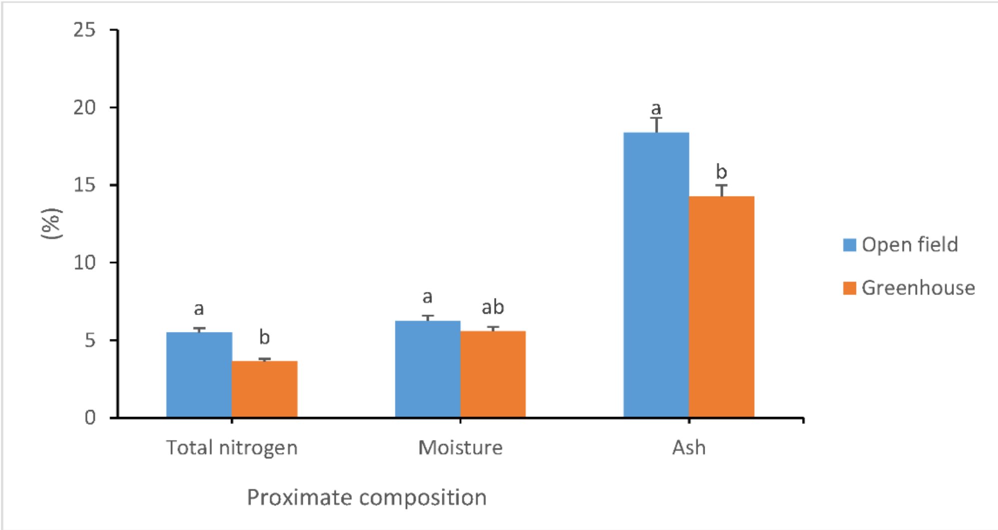

Figure 3. A comparative diagram showing the differences in proximate composition of *A. Graecizans* L. under open field (blue) versus greenhouse (orange) conditions a referrer to open field whilst b referrers to greenhouse.

Table 4. Proximate composition of *A. Cruentus* L. in the open field vs. greenhouse on a dry weight basis (%).

	Total Nitrogen	Moisture	Ash
Treatments			
Open field	523 [a]	5.61 [a]	19.50 [a]
Greenhouse	3.37 [b]	5.26 [a]	16.17 [a]
rep	3	3	3
d.f.	4	4	4
SEM	0.0219	0.1341	0.295
SED	0.0309	0.1896	0.418
LSD (5%)	0.0858	0.5265	1.160
F probability	<0.001	0.139	0.001

SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

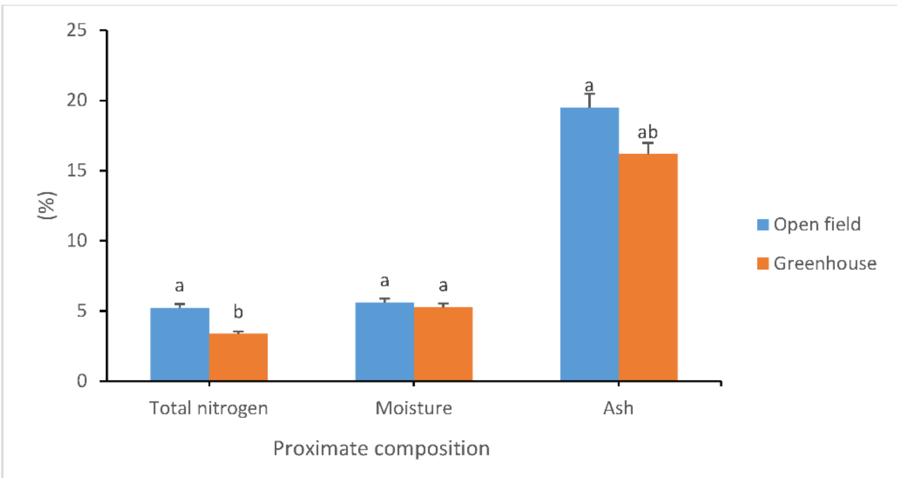

Figure 4. A comparative diagram showing the differences in proximate composition of *A. Cruentus* L. under open field (blue) versus greenhouse (orange) conditions a referrer to open field whilst b referrers to greenhouse.

3.3. Mineral Composition

Our study revealed that there was a significant difference ($p \leq 0.01$) in the content of calcium, magnesium, phosphors, iron, zinc, aluminium, copper and manganese, with higher values in the open field cultivation as shown in Table 5 and Figure 5. On the contrary, the content of potassium, sodium, boron and sulphur were significantly higher in the greenhouse cultivation. The means of the analysis of variance of *A. Cruentus* showed significant differences ($p \leq 0.01$) (* see Table 6) among the two cultivation systems. The highest content of Ca, Mg, P, Fe, Zn, Al, B, Cu and Mn were observed in plant material from the open field cultivation. However, the content of sodium detected in *A. Cruentus* did not differ significantly ($p \leq 0.01$) between both the open field and greenhouse cultivations. Notably, the greenhouse cultivation system exhibited significant variations in the content of potassium and sulphur as compared to the open field cropping system as shown in Table 6 and Figure 6.

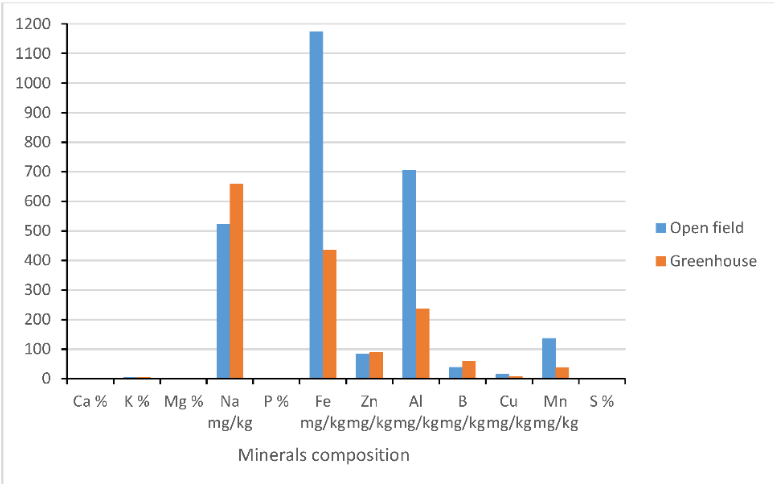

Figure 5. A comparative diagram showing the differences in mineral composition of *A. Graecizans* L. under open field (blue) versus greenhouse (orange) conditions, a referrer to open field whilst b referrers to greenhouse.

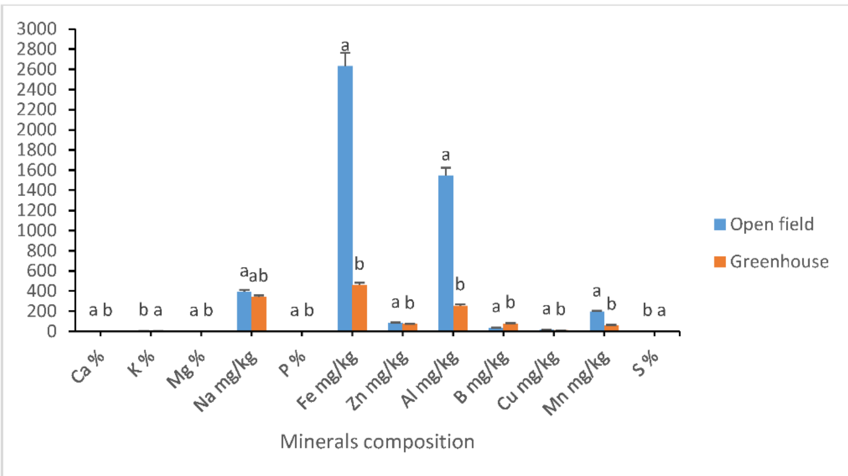

Figure 6. A comparative diagram showing the differences in mineral composition of *A. Cruentus* L. under open field (blue) versus greenhouse (orange) conditions, a referrer to open field whilst b referrers to greenhouse.

Table 5. Comparison of minerals composition of amaranth leaves *A. Graecizans* L. in the open field vs. greenhouse on a dry weight basis.

	Calcium	Potassium	Magnesium	Sodium	Phosphorus	Iron	Zinc	Aluminium	Boron	Copper	Manganese	Sulphur
Treatments	%	%	%	mg/kg	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
Open field	2.41 [a]	4.34 [b]	1.66 [a]	522.4 [b]	0.82 [a]	1174.7 [a]	85.5 [a]	705 [a]	38.37 [b]	15.57 [a]	137.00 [a]	0.56 [b]
Greenhouse	1.72 [b]	4.76 [a]	1.03 [b]	659.8 [a]	0.50 [b]	434.3 [b]	88.4 [b]	237 [b]	59.90 [a]	8.48 [b]	37.60 [b]	0.78 [a]
Rep	3	3	3	3	3	3	3	3	3	3	3	3
d.f.	4	4	4	4	4	4	4	4	4	4	4	4
SEM	0.00943	0.01106	0.00471	3.51	0.00275	8.38	1.86	20.1	1.356	0.402	1.155	0.000943
SED	0.01333	0.01563	0.00667	4.97	0.00389	11.85	2.63	28.5	1.918	0.568	1.633	0.001333
LSD (5%)	0.03702	0.04341	0.01851	13.80	0.01079	32.91	7.29	79.0	5.324	1.577	4.534	0.003702
F probability	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.336	<0.001	<0.001	<0.001	<0.001	<0.001

SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

Table 6. Comparison of mineral composition of *A. Cruentus* L. in open field vs. greenhouse on a dry weight basis.

	Calcium	Potassium	Magnesium	Sodium	Phosphorus	Iron	Zinc	Aluminium	Boron	Copper	Manganese	Sulphur
Treatments	%	%	%	mg/kg	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
Open field	2.40 [a]	4.02 [b]	1.71 [a]	392.0 [a]	0.73 [a]	2633 [a]	83.10 [a]	1547 [a]	36.20 [a]	17.30 [a]	194.63 [a]	0.52 [b]
Greenhouse	2.03 [b]	5.07 [a]	1.23 [b]	341.0 [a b]	0.47 [b]	460 [b]	71.87 [b]	255 [b]	77.90 [b]	10.27 [b]	60.27 [b]	0.66 [a]
Rep	3	3	3	3	3	3	3	3	3	3	3	3
d.f.	4	4	4	4	4	4	4	4	4	4	4	4
SEM	0.01247	0.0217	0.01202	7.88	0.00340	93.4	0.377	62.5	1.142	0.197	1.259	0.00337
SED	0.01764	0.0307	0.01700	11.15	0.00481	132.1	0.533	88.4	1.615	0.279	1.780	0.00477
LSD (5%)	0.04897	0.0853	0.04719	30.96	0.01335	366.8	1.481	245.5	4.482	0.774	4.942	0.01325
F probability	<0.001	<0.001	<0.001	0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

SEM is the standard error of means. SED is the standard error of difference. LSD is the *t*-test least significant difference at the 5% level. Means within columns followed by the same lower-case letter did not differ significantly.

4. Discussion

The recent interest in *Amaranthus* species stems from its high level of genetic diversity, phenotypic plasticity, extreme adaptability to adverse growing conditions and climate resilience [44]. Amaranth is one of the easiest plants to grow in agriculturally marginalized lands and can be a solution for improving food security and food nutritional quality [45]. Several studies were conducted on the production of various *Amaranthus* species, all of which were grown in the open field, however there are few studies on amaranth cultivation in the greenhouse with no and/or few scientific literature recorded. A study by [46] on the chlorophyll content evaluated in GA-2 and RA *Amaranthus* species in open-field and greenhouse cultivations, revealed that field-grown plants possessed a significantly higher amount of chlorophyll content. Their findings are in agreement with the results of our study, where the open field cultivation had the highest leaf chlorophyll content and leaf area for the *Amaranthus* species. In addition, a study to observe the performance and fruit quality of *Cucumis melo* in both the greenhouse and field conditions revealed that the field experiment and inoculation used improved the fruit production and quality [47]. Leaf color is regarded as the primary and immediate indicator of plant performance and purchasing power of consumers [48]. Traits such as leaf size, leaf color, type and intensity of greenness are associated with yield and can be useful in the selection for breeding, as enhancements of these traits also improves marketability and consumer preference [13]. In our study, a low chlorophyll content on the leaves was observed in the greenhouse-grown *Amaranthus* species, which may be associated with factors such as plant nutrition deficiency and environmental stresses [49] that may have affected the greenness of the leaves, resulting in low branching and pale green small leaves with short/medium plant heights. Broader vegetable leaves are also expected to increase light interception, potentially leading to an increased production of photosynthates. However, [50] disagree on the basis that the higher the number of the leaves yield to shorter/smaller leaf areas or leaf area index, which could imply that most leaves are shaded, thereby yielding little photosynthesis [51].

Amaranthus, unlike Swiss chard and cabbage, cannot withstand low temperatures. All amaranth species prefer warm temperatures and can thrive above 25 °C-day temperatures, however, not lower than 15 °C for the night temperature [22]. In our study, lower night temperatures of 7.4 °C in a greenhouse cultivation could have been the reason for the low leaf chlorophyll content and number of leaves due to chilling injuries, thereby making the amaranth leaves fibrous and bent as reported by [18]. Moreover, due to the closed environment and the design, the relative humidity and day temperatures were higher in the greenhouse conditions than in the open field. This was observed in the present study where the temperature in the greenhouse reached a maximum of 44.9 °C during the day contrary to the maximum temperature of 32 °C in the open field where the study was conducted.

The number of leaves per plant is an important variable to consider when comparing the potentials of plants [52]. From our study, greenhouse-grown *A. cruentus* had 27.33 recorded as the number of leaves, which was similar to that obtained by [53], which ranged from 18.92–37.11 in salinity tolerance. On the contrary, the results obtained by [6] are not in agreement with our findings, where *A. hypochondriacus* reported an average of 35 leaves in an open field cultivation system.

The stem height of A. *Graecizans* grown in a greenhouse cultivation had a significantly taller stem height (* see Table 1), however, a non-significant difference was observed in the leaf area, number of leaves and stem height of *A. cruentus* plants grown in both two-cropping environments as shown in Table 2. A similar observation of taller stem heights in greenhouse-grown plants was made in a study by [46] using photosynthetic phenomics of field- and greenhouse-grown *Amaranthus* species. Greenhouse-grown plants (GA-2 and CC) were generally taller than the field grown plants, which is in agreement with the experiment measurements on the availability of PAR in the greenhouse.

Ref. [6] compared the growth of amaranth (*Amaranthus hypochondriacus*) between greenhouse and open field systems, and the findings revealed that the average height of the greenhouse plants was greater than reported in various open field studies. In a different experiment by [54], which included the application of salicylic acid foliar as a treatment, the highest growth parameters such as the number of leaves and stem height of tomato plants were recorded in the greenhouse cultivation. Similar findings were observed by [55] who concluded that the yield performances (plant height, leaf weight, stem weight) of *Amaranthus* PLR 1 was better under a polyhouse and under a shade net as compared to open conditions during the rainy and summer seasons. In another study, the stem height growth of different *Amaranthus* species was observed to be slow in an open field experiment [56]. However, notably in the study by [37] on the comparison of the growth and nutritional composition of selected exotic and indigenous *Amaranthus* cultivars under the root-knot nematode infestations, the exotic cultivar 'Tanzania' had a higher plant height/stem diameter in the field conditions.

Plant/stem height is reported to be a quantitative character controlled by numerous genes and is easily affected by environmental conditions [57]. As a result, [58] reported that under the outdoor environment, high wind speed could cause slight bending of the plants, and this could lead to variations in the height measurements. Should the height range from 50 to 150 cm, it could easily and strongly be branched from the lower part, which supports the findings observed in this study as shown in Table 1.

Greenhouses are known to provide favorable plant conditions. On the contrary, in the open field, environmental conditions are much more variable, forcing plants to adapt in order to survive. In this study, concentrations of the various proximate and mineral composition were found to be largely influenced by the cultivation system. For instance, the open field cropping system had a significant impact on both the red and green species of *Amaranthus* analyzed. The findings showed that a significant amount of Ca, Mg, P, Fe, Zn, Al, B, Cu and Mn minerals was recorded in amaranth grown in the open field, whilst K, Na, B and S were observed in the greenhouse-grown *A. Graecizans* species (* see Table 5). In Table 6, the open-field-grown *A. Cruentus* amaranth species showed a great amount of minerals in its composition, such as Ca, Mg, P, Fe, Zn, Al, B, Cu and Mn, while K and S were found in the greenhouse-grown *A. Cruentus* plants. However, there was no significant difference between the two cropping systems on sodium content.

A study by [59] suggested that a greater amount of calcium and iron was found in the leaves of amaranth plants which grow under warm to hot conditions, compared to those which grow under cool conditions (greenhouse), in consideration of the plant age. In addition, high levels of calcium and iron have been reported in green accessions of amaranth compared to light green accessions [13]. In the present study, high levels of calcium were reported in the open-field-grown A. *Graecizans* plants, which is a green accession of amaranth.

The results from the current study on mineral composition are in accordance with the findings of [60], which revealed that compared to the field-grown mature foliage of tropical spinach (*Amaranthus* sp.) and Roselle (*Hibiscus sabdariffa* L.), greenhouse-grown micro/baby-greens were lower in Ca but higher in P, K, Mg, Fe, Mn and Zn. On the contrary, a study by [61] evaluating the minerals and ascorbic acid concentrations of greenhouse- and field-grown bell pepper, cucumber and tomato revealed that K, P and Mg concentrations in greenhouse-grown bell pepper, cucumber and tomato were greater than expected levels and lower in the open field cultivations. Field-grown vegetables had lower contents of Cu, Mn, Fe, Zn and ascorbic acid compared to greenhouse-grown vegetables. According to [61], the reason for the elevated concentrations of K, P and Mg in the greenhouse-grown cucumber, tomato and bell pepper might be attributed to poor fertilizer management and a high application of manure and synthetic fertilizers. Similarly, green morph amaranth was found to contain an abundant moisture content, with notable levels of inorganic minerals including K, Ca, Mg, Fe, Mn, Cu and Zn.

Ref. [62] indicated that the high ash content can be an indication of calcium, aluminium, manganese or iron deposition on the activated carbon or the presence of sand. According to [63], low sodium content makes it acceptable for people with high blood pressure and kidney problems. At the same time, sodium is a vital intracellular and extracellular cation which assists in the regulation of plasma volume and acid-based balance during nerve and muscle contraction [64]. Moreover, several minerals were noted to be a key for regulating water balance in different compartments of the body; the most important of these are sodium, potassium and chloride [65].

Whilst Fe is an important element in the biofortification of crops, it is responsible for the formation of chlorophyll in plants [66] and is essential for blood production in humans. An abundance of calcium and gluten-free proteins makes amaranth a suitable diet for newly diagnosed celiac patients, to aid in bone metabolism and relieve complications in the intestine [67]. According to [68], the consumption of African leafy vegetables can contribute to 50–75% of the recommended daily intake of more than 400 g per person, to protect against micronutrient deficiencies (vitamin A, iron and zinc) mostly in children and pregnant women and non-communicable diseases. It is evident that the consumption of indigenous leafy vegetables, i.e., *Amaranthus* species, can play a significant role in households' livelihoods through improving food and nutrition as a provision of an important source of essential minerals. As a result, the pharmacological evaluation of seeds and leaf extracts of amaranth revealed the potency of its bioactive compounds in suppressing terminal diseases [27] such as diabetes, hyperlipidaemia, anti-helminthic, antimalarial, anti-inflammatory and antifungal characteristics, and malnutrition related matters [69]. Future studies are recommended in which organic and chemical fertilizers in both open and greenhouse cultivation systems should be used, to determine the production and nutritional composition potential of commonly consumed amaranth species.

5. Conclusions

Amaranthus is a leafy vegetable of interest to answer a mounting demand for food and plays an important role in sustaining food security and alleviation of malnutrition in South Africa. Similar to maize, wheat, sorghum, barley, rice and soybean, amaranth has a high potential for economic exploitation and because of its easy growing habit and nutritional value for both grains and leaves, it is considered a new promising food for the future. The results of this study demonstrated that its growth parameters and nutrient accumulation is greatly influenced by the planting conditions and amaranth species. In the conditions evaluated, the growth parameters, proximate composition and essential minerals of open field cultivated amaranth plants of both species performed better than greenhouse-grown ones. The differences observed could be attributed to both environmental and genetic factors, which may have influenced the plant physiological parameters and nutritional composition of the amaranth species. Amaranth species have a higher nutrition composition than commonly domesticated vegetables such as cabbage, spinach and Swiss chard, and can provide essential minerals, proximate composition and energy/nutrition requirements to the daily diet of vulnerable groups in rural communities. Therefore, this implies that choosing a suitable condition to grow *Amaranthus* will influence the important nutrients needed for human health. From the findings of this study, it is concluded that *Amaranthus* species grown in the open field had high mineral compositions for minerals such as Ca, P, Mg, Fe, Zn, etc. whilst K, B, Na and S were highly prevalent in the greenhouse cultivation. If Amaranth species is to be grown for medicinal and/or health purposes, open field cultivation would be ideal. On the other hand, greenhouse cultivation would be ideal for higher yields due to the high number of leaves recorded on both species (*A. Graecizans* L. and *A. Cruentus* L.).

Author Contributions: Conceptualization, G.M.M. and L.E.N.; methodology, L.E.N.; software, L.E.N.; validation, G.M.M. and L.E.N.; formal analysis, L.E.N.; investigation, G.M.M.; resources, G.M.M. and L.E.N.; data curation, G.M.M.; writing—original draft preparation, G.M.M.; writing—review and editing, G.M.M. and L.E.N.; visualization, L.E.N.; supervision, L.E.N. project administration, G.M.M. and L.E.N.; funding acquisition, G.M.M. and L.E.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Department of Agriculture and Animal Health, and approved by the UNISA-CAES Health Ethics Committee) of University of South Africa (REC Reference#:2021/CAES_HREC/131 issued on 6 September 2021).

Data Availability Statement: Data supporting will be provided upon request when under review.

Acknowledgments: The authors would love to extend massive gratitude and appreciation to the University of South Africa, Horticulture Center managerial staff for permitting us to conduct the experiment, providing us with the necessities and assisting whenever needed. We also extend our appreciation to the Agricultural Research Council for Soil, Climate and Water for analyzing the nutritional composition of *Amaranthus* species.

Conflicts of Interest: The authors declare no conflict of interest. Both authors have read and agreed to the published version of the manuscript.

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