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Characterization of Nutritional Potential of *Amaranthus* sp. Grain Production

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Abstract: The growing demand for nutritious foods has spurred investigations into alternative sources of nutrition beyond traditional options. For this reason, the present study approaches amaranth, which is a plant with high nutritional potential. Based on the unique pedoclimatic conditions of the Somes meadow in Transylvania and the known adaptability of amaranth varieties to diverse environments, we hypothesize that certain amaranth varieties of South American origin will demonstrate their potential for morphological development, grain biomass yield, and quantitative characteristics when cultivated in this specific environment. Our study aims to identify if, based on morpho-productive traits, the six amaranth varieties under investigation in a specific environment are suitable for consumption as functional food. A bifactorial trial was implemented with the following factors: amaranth species and amaranth varieties. Two species and seven varieties of amaranth were studied. Differences are reported between morpho-productive and quantitative traits of the seven amaranth varieties studied in this research. The Pearson simple correlations show that morphological traits moderately contribute to grain fresh biomass yield, while morphological traits and fresh biomass strongly contributed to grains dry biomass yield. Our study shows that while current research offers valuable perspectives on the performance and nutritional composition of amaranth varieties studied, there are recommended more studies conducted across diverse environments.

Keywords: morpho-productive traits; functional food; grains; interrelationships; pseudocereals

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1. Introduction

The increasing demand for healthy foods has led to the exploration of alternatives to the usual nutritional sources [1]. One such alternative is amaranth, a pseudocereal known for its nutritional benefits and functional food potential [2]. Pseudocereals, like amaranth, are grains with high protein content and no gluten, offering similar traits to traditional cereals. Originating from South America, *Amaranthus* sp. boasts nearly 60 species, with some varieties used fresh in salads and soups, and others in the food industry to enhance flavor and nutrition [3–6].

The functional foods enrich offerings due to their exceptional nutritional profile and versatile culinary uses [4]. Amaranth products can enrich functional food offerings due to their high protein content, gluten-free nature, and rich array of essential nutrients. Also, amaranth's adaptability in various food products, including cereals, snacks, and baked goods, offers manufacturers opportunities to create innovative, health-focused products that cater to evolving consumer preferences for nutritious and sustainable food options [7].

Some amaranth varieties of leaves (i.e., *A. blitum*, *A. cruentus*, *A. dubius*, *A. edulis*, *A. hypochondriacus*, *A. tricolor*) may be used, fresh, in salads and soups. Seeds from some varieties (i.e., *A. caudatus*, *A. cruentus*, *A. hybridus*, *A. hypochondriacus*, *A. mantegazzianus*) are used as raw material in the food industry, or for enhancing the flavor and nutritional value of various food items such as bread, cookies, cakes, etc. [8]. Other varieties (i.e., *A. retroflexus*, *A. spinosus*, *A. viridis*) are not edible for humans or animals [7]. Recognized by experts as a future-forward plant, amaranth's genetic diversity and adaptability make it suitable for challenging environmental conditions [9,10]. Studies have shown its potential to lower cholesterol levels due to compounds like phytosterols found in its fats and soluble fibers [11,12].

Amaranth grains are used in monogastric feed (broilers, rabbits, and pigs) [13]. Studies conducted on rabbits and pigs show an increase in rabbit meat dry matter, protein, and fat contents [14], and pig meat dry matter [15]. The grains are also used in human nutrition as flakes, flour, or even as a source of functional drinks [13,16]. Amaranth flour can replace wheat flour entirely or partially, and may be used for preparing a large diversity of food, such as pasta, cookies, breads, porridge, etc. [17–19].

In terms of nutrition, amaranth stands out for its high protein content, superior to many other grains, and it contains all essential amino acids, including lysine, which is often lacking in other grains. Rich in both soluble and insoluble fiber, amaranth supports digestive health, aids in satiety, and may help lower cholesterol [20–24].

Additionally, amaranth is a good source of vitamins such as A, C, E, and various B vitamins, crucial for metabolism, skin health, and immune function. Its mineral content, including iron, calcium, and zinc, supports bone and muscle health [21,25]. Being gluten-free, amaranth serves as an alternative grain for those with gluten intolerance. Its fatty acid profile, with primarily unsaturated fats, is beneficial for heart health [13,23]. It is low in saturated fatty acids (C16:0, C18:0), but amaranth oil contains up to 73% primarily unsaturated fatty acids (PUFA), which are beneficial for heart health when consumed in moderation [24].

Amaranth is considered a functional food because it is a valuable source of antioxidants, including phenolic compounds and flavonoids, which help protect the body against oxidative stress and reduce the risk of chronic diseases such as heart disease and cancer [22–26]. The total polyphenolic content of amaranth may vary depending on factors like variety, growing conditions, and processing methods. Amaranth contains rutin, quercetin, kaempferol, which are flavonoids known for their antioxidant, anti-inflammatory, and immune-modulating effects. It also contains caffeic and gallic acids, which are phenolic acids with antioxidant properties that may help protect against oxidative damage [27–29]. Often, total polyphenolic content (TPC) is expressed as gallic acid equivalents (GAE/g). Studies assessing the total polyphenolic content of amaranth have reported varying concentrations from 1.04 up to 14.94 mg GAE/g dry matter; thus, amaranth is considered a good source of polyphenols [30,31]. The exact content can depend on factors such as the part of the plant analyzed (seeds, leaves, or stems), the variety of amaranth, and the methods used for extraction and analysis [22,32].

The description of quantitative and productive traits of amaranth contributes to emphasize its suitability as a functional food, mainly in present global context characterized by the population changing in terms of dietary preferences focused on healthy nutrition. Testing amaranth varieties in terms of yields is of interest for promoting improvement of their productivity. The present study is focused on identifying the suitability of six amaranth varieties, cultivated in a specific environment, to be used in consumption as functional food. In this aim, we comparatively present their morphological development, grain biomass yield, and quantitative characteristics. Our study also provides context regarding the suitability of cultivation of amaranth varieties of South American origin in the specific pedoclimatic conditions of Somes meadow in Transylvania. The novelty of our study lies in examination of amaranth varieties within a specific geographical context different of their origin, offering insights into their potential as functional food sources in specific Romanian pedoclimatic conditions. By emphasizing their suitability for consumption, the research paves the way for informed dietary choices and agricultural practices tailored to local conditions.

2. Materials and Methods

The research was performed in a private farm from Somes meadow, Mireșu Mare commune (47º29′16″ N, 23º21′26″ E). The regional specific 30 years mean temperature is 8–9 °C, with 700–800 mm mean annual rainfall [33]. Phaeozem soil [34] characterizes the experimental field. It is a fertile (with high humus content of 3.20–4.45%) weak acidic (pH = 6.00–6.35) loam clay soil (45.00–56.00% clay).

A bifactorial trial was implemented with factors amaranth species and amaranth varieties. Two amaranth species and six varieties were studied (Figure 1): Alegria and Amont (*Amaranthus cruentus* L. species), and Golden, Mercado, Hopi Red Dye, and Opopeo (*Amaranthus hypochondriacus* L. species).

Alegria Amont Golden

Mercado Hopy Red Opopeo

Figure 1. The studied amaranth species and varieties.

No action against disease and weed was necessary. The experiment was conducted during the period of 23 March–16 September 2023. The seeds were sown at a depth of 0.5 cm, with plant density of 70,000 plants/ha, in three repetitions, on an experimental field of 6000 m^2, with plots of 250 m^2, for each repetition and variety. The distance between rows was 50 cm, and the distance between plants was 10 cm. Tap water was used for watering, which was performed during June–August, at two-week intervals, to sustain soil moisture at field capacity. Fertilization was made by application and mixed with the soil and cattle manure at a rate of 2 t/ha, in the autumn of 2022. The grains were separated from the panicles manually by shaking, then collected in collection recipients. At the end of experimental period, the morpho-productive traits (stem height, number of leaves, grain fresh and dry biomass yields) and quantitative (grain dry matter, crude protein, crude ash, crude fat, crude fiber, non-nitrogen extractives and TPC) traits were examined, along with their interactions.

The crude chemical composition of amaranth grains was examined according to laboratory methodology proposed by Șara and Odagiu [35]. Dry matter was determined gravimetrically by drying in an oven at 105 °C, crude protein was determined using the Kjeldahl method (wet digestion with sulfuric acid, and distillation with sodium hydroxide), crude fiber by double hydrolysis (acid with sulfuric acid 1%, and sodium hydroxide 1%), crude fat using the Soxhlet method by hot extraction with petroleum ether, and crude ash gravimetrically by calcination at 550 °C. The nitrogen-free extracts were calculated as percentages; the function of the above-mentioned crude components was determined by their subtraction from 100 [35]. The TPCs were quantified according to the Folin–Ciocâlteu method, as gallic acid equivalents—mg GAE/g grains [29]. All samples were analyzed in 10 replicates.

SPSS Statistics v28, STATISTICA v. 8.0, and XLSTAT Version 2022.2.1 were used for statistical data processing. Basic statistics with its components of descriptive statistics and correlations calculation was implemented for the mean, and the standard error of mean calculation, together with simple Pearson correlations between green and dry biomass yields, was calculated for each experimental variety. Multivariate analysis (Clustering, Factorial Analysis through its component Principal Components Analysis PCA) and multiple regression were implemented for emphasizing the interrelations between fresh and dry biomatter yields, and influence of morphological and quantitative traits on fresh and dry biomatter yields.

3. Results

3.1. The Morpho-Productive Traits of Six *Amaranthus* sp. Varieties

The plant heights rangefrom 79.33 cm (Opopeo variety) to 101.33 cm (Amont variety), while the number of leaves range from 21.67, corresponding to the Amont variety, to 32, corresponding to the Alegria variety (Table 1). No significant differences ($p > 0.05$) are found between mean plant heights belonging to the Amont, Mercado, and Hopy Red Dye varieties on one hand, and between Alegria and Golden, on the other hand. The mean plant height observed in Opopeo differs ($p < 0.05$) from the mean plant heights reported for all other five *Amaranthus* sp. varieties. No differences are observed between the mean number of leaves corresponding to Alegria and Mercado. Between the mean number of leaves of Golden and Hopy Red Dye varieties, no significant differences are observed. The Amont variety shows the smallest mean number of leaves, which significantly differs from the means reported for the other five studied varieties. The mean number of leaves observed in Opopeo also differs significantly from the means reported for all other varieties of *Amaranthus* sp.

Table 1. The mean plants heights and leaves number of *Amaranthus* sp. varieties.

Variety	Plants Height (cm)	Number of Leaves
Alegria	86.00 ± 0.76 b	32.00 ± 0.93 b
Amont	101.25 ± 2.62 a	21.71 ± 0.69 d
Golden	84.48 ± 1.62 b	23.55 ± 0.71 c
Mercado	98.33 ± 0.95 a	31.67 ± 0.76 b
Hopy Red Dye	99.00 ± 1.23 a	24.46 ± 0.75 c
Opopeo	79.35 ± 1.23 c	27.39 ± 1.17 a

The differences between any two yield averages are significant, if their values are followed by letters, or groups of different letters.

Table 2 shows the mean values of green and dry biomass yields of the studied *Amaranthus* sp. varieties. The lowest means of both green and dry biomass yields are observed in Amont (19,432.60 kg green biomass/ha, and 6603.20 kg dry biomass/ha, respectively), while the highest are observed in Alegria (2948.60 kg green biomass/ha, and 10,068.06 kg dry biomass/ha, respectively). Similar mean green biomass yields are observed in Alegria and Mercado, but also between Hopy Red Dye and Opopeo. Significant differences are seen between the Amont mean green biomass yield and mean yields corresponding to the other studied varieties. No significant differences are found between mean dry biomass yields of the Hopy Red Dye and Opopeo varieties, but between the mean dry biomass yields of the above-mentioned varieties and those corresponding to all other *Amaranthus* sp. varieties, significant differences are observed.

Table 2. The mean green and dry biomass yield of *Amaranthus* sp. varieties.

Variety	Green Biomass Yield (kg/ha)	Dry Biomass Yield (kg/ha)
Alegria	25,948.60 ± 8.21 a	10,068.06 ± 10.69 a
Amont	19,432.60 ± 7.52 b	6603.20 ± 8.59 b
Golden	20,886.80 ± 7.21 c	7542.22 ± 8.37 c
Mercado	25,690.60 ± 8.89 a	9831.79 ± 13.51 d
Hopy Red Dye	22,676.60 ± 7.68 d	8279.23 ± 9.62 e
Opopeo	22,817.21 ± 5.68 d	8371.56 ± 13.41 e

The differences between any two yield averages are significant, if their values are followed by letters, or groups of different letters.

The mean fresh and dry grain yields are presented in Table 3. The highest fresh grain yield of 2768.60 kg/ha corresponds to Alegria, while the lowest yield of 2277.80 kg/ha corresponds to the Amont variety. The Alegria and Mercado varieties show similar fresh grain yields among all *Amaranthus* sp. varieties. Also, between fresh grain yields corresponding to Hopy Red Dye and Opopeo, no significant yields are observed. The mean fresh grain yield reported in Amont, on one hand, and mean fresh grain yield reported in Golden, on the other hand, differ significantly from mean yields reported for the other studied varieties. In the Alegria variety, the highest mean dry grain yield (2270.86 kg/ha) is reported, and in Amont, the lowest (1843.26 kg/ha). Similar dry grain yields are observed in the Golden, Hopy Red Dye, and Opopeo varieties. Significant differences are reported between dry grain yields corresponding to Alegria, Amont, and Mercado on one hand, and between the above-mentioned varieties and Golden, Hopy Red Dye, and Opopeo, on the other hand.

Table 3. The fresh and dry grain mean yields of amaranth varieties.

Variety	Fresh Grain Yield (kg/ha)	Dry Grain Yield (kg/ha)
Alegria	2768.60 ± 10.22 a	2270.86 ± 20.05 a
Amont	2277.80 ± 7.23 b	1843.26 ± 13.41 b
Golden	2407.80 ± 9.85 c	1939.90 ± 17.47 c
Mercado	23,5790 ± 4.03 a	2187.36 ± 16.08 d
Hopy Red Dye	2650.20 ± 11.19 d	1949.39 ± 5.95 c
Opopeo	2612.00 ± 9.93 d	1982.90 ± 12.77 c

The differences between any two yield averages are significant, if their values are followed by letters, or groups of different letters.

3.2. The Relationships between Morpho-Productive Traits of Six Amaranthus sp. Varieties

We correlated the dry biomass and dry grain yields (Figure 2, Tables 4 and 5). The correlations are strong, very strong (with values represented in red in Table 4), and significant ($p < 0.05$) for the Amont, Golden, Hopy Red Dye, and Opopeo varieties (Tables 4 and 5).

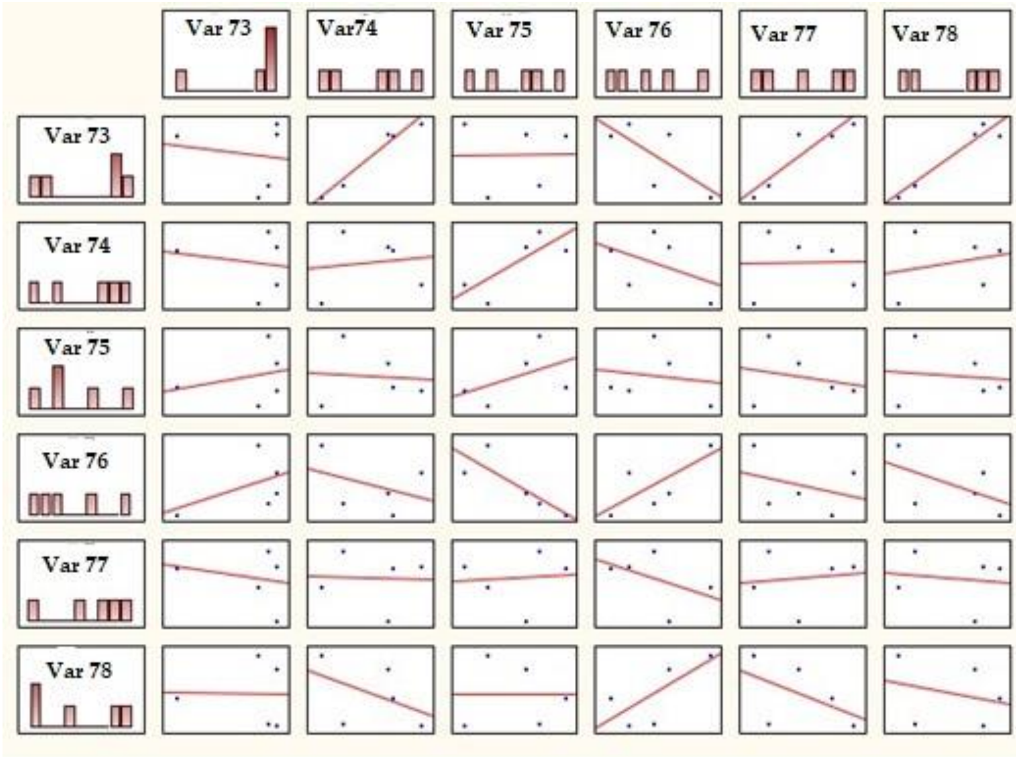

Figure 2. The Scatterplot Pearson simple correlation matrix between biomass and grain yields for varieties. Var 66, 73—Alegria, Var 67, 74—Amont, Var 68, 75—Golden, Var 69, 76—Mercado, Var 70, 77—Hopi Red Dye, Var 71, 78—Opopeo.

Table 4. The correlation matrix between dry biomass and dry grain yields.

Variety	Alegria	Amont	Golden	Mercado	Hopy Red Dye	Opopeo
Alegria	1	0.485	0.768	0.486	0.471	0.551
Amont		1	0.420	0.845	0.994	0.922
Golden			1	0.411	0.484	0.504
Mercado				1	0.844	0.911
Hopy Red Dye					1	0.950
Opopeo						1

Table 5. The matrix of *p* values between dry biomass and dry grain yields. Violet signifies total correlation; Green signifies very weak correlations; Blue signifies weak correlations; Dark blue signifies strong correlations.

Variety	Alegria	Amont	Golden	Mercado	Hopy Red Dye	Opopeo
Alegria	1	0.847	0.983	0.172	0.833	0.745
Amont		1	0.114	0.044	0.039	0.033
Golden			1	0.802	0.718	0.856
Mercado				1	0.046	0.031
Hopy Red Dye					1	0.024
Opopeo						1

According to the dendrogram, fresh and dry grain yields are grouped in two principal clusters, A and B, respectively (Figure 3). Cluster A groups the Alegria, Hopy Red, and Opopeo varieties, which show high similarity of components as a consequence of their highest fresh yields. Cluster B is divided into two subclusters, B1:1 and B1:2, and is made up of nine components. Subcluster B1:1 is the largest one and contains five components; it is the most diverse because it groups both dry and fresh grain yields. The Amont, Golden, and Mercado fresh grain yields exhibit high similarity with Alegria and Mercado dry yields.

The second subcluster, B1:2, groups four dry grain yields corresponding to Amont, Golden, Hopy Red, and Epopee.

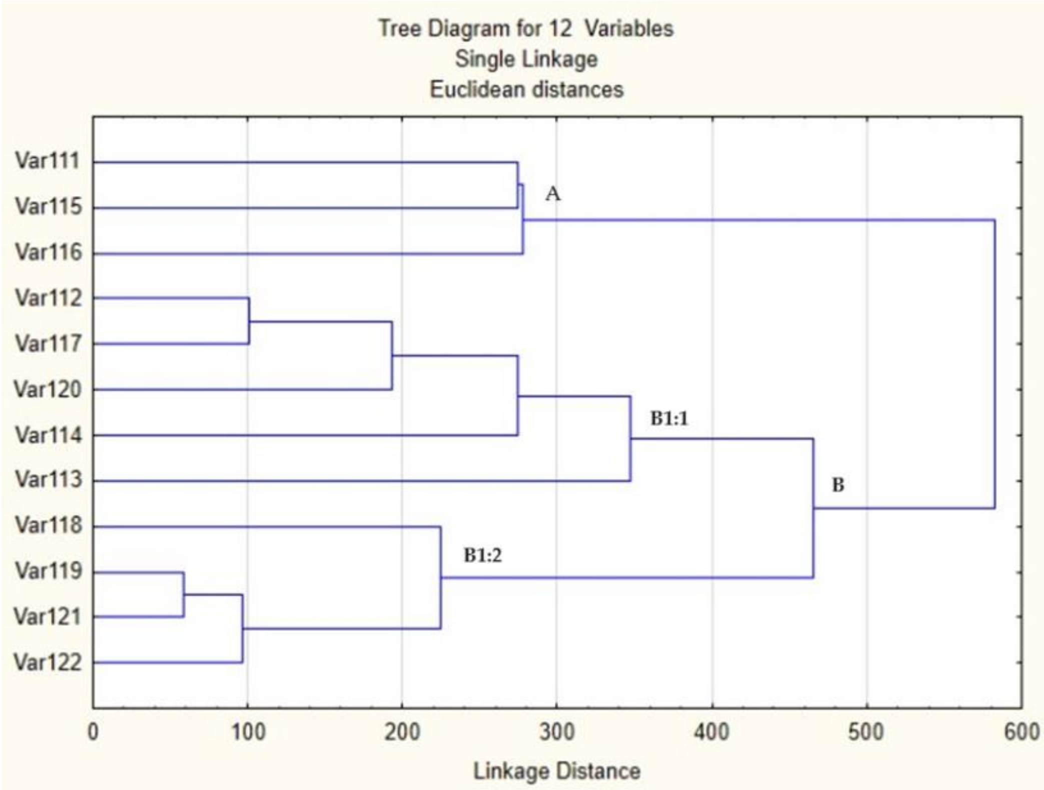

Figure 3. The dendrogram of the clusters of fresh and dry grain yields. Var 111, 117–Alegria, Var 112, 118–Amont, Var 113, 119–Golden, Var 114, 120–Mercado, Var 115, 121–Hopi Red Dye, Var 116, 122–Opopeo.

Within PCA, the biplot representation shows two factors that are the principal informative components of the analysis. Factor 1 (productivity) is responsible for 62.04% of variance, while Factor 2 (variety) is responsible for 37.96% of variance (Table 6, Figure 4).

Table 6. The Eigenvalues and total variance.

Nr. crt.	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative %
1	7.044883	62.04069	7.044883	62.04069
2	4.310378	37.95931	11.35526	100.0000

Factor 1 (productivity) is correlated with the dry grain yield reported for Mercado and Hopy red varieties (Figure 4), while Factor 2 is correlated with the Alegria and Mercado fresh and dry grain yields, Hopy Red Dye dry grain yield, and Opopeo fresh grain yield. Neither factor is correlated with Amont fresh and dry grain yields, and the Golden fresh grain yield. A major group, corresponding to dry grain yields of the Alegria, Golden, Mercado, and Hopy Red Dry varieties is correlated with variety (red circle), while other, corresponding to the Amond fresh and dry yields and Golden fresh yield, is negatively correlated with productivity (blue circle).

For emphasizing the influence of morphological traits (plant height and number of leaves) on biomass and grains yields, multiple correlations were calculated for each of the analyzed *Amaranthus* sp. varieties (Tables 7 and 8).

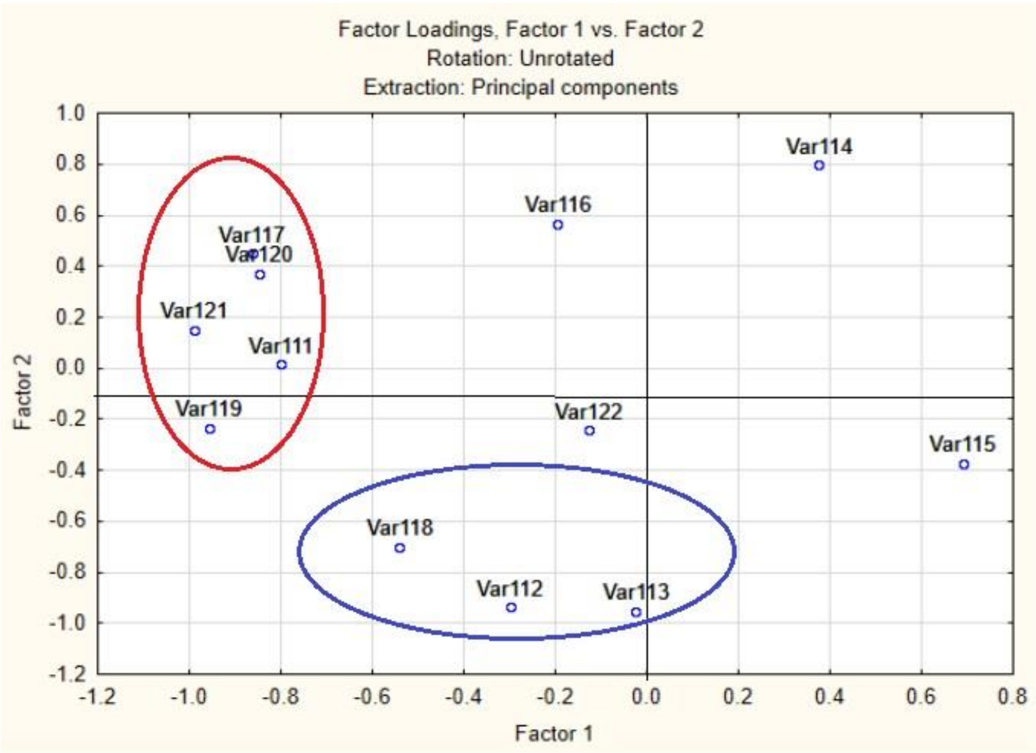

Figure 4. The biplot representation in projection plans of fresh and dry grain yields.Var 111, 117. –Alegria, Var 112, 118–Amont, Var 113, 119–Golden, Var 114, 120–Mercado, Var 115, 121–Hopi Red Dye, Var 116, 122–Opopeo.

Table 7. The multiple regression analysis of dry biomass yield, plant heights, leaves, and number of varieties.

Variety	N	Regression line	r	r^2	p
Alegria	10	Y = 1008.021–0.078X1 + 0.347X2	0.343	0.117	0.882
Amont	10	Y = 6304.343–0.227X1 + 0.216X2	0.223	0.049	0.950
Golden	10	Y = 7563.559–0.084X1 + 0.5575X2	0.284	0.080	0.892
Mercado	10	Y = 9418.051–0.159X1 + 0.493X2	0.431	0.186	0.813
Hopy Red Dye	10	Y = 8266.946–0.146X1 + 0.501X2	0.478	0.228	0.771
Opopeo	10	Y = 9195.162–0.258X1 + 0.556X2	0.419	0.175	0.805

Y—dry biomass yield; X1—plants heights; X2—leaves number.

Table 8. The multiple regression analysis of dry seed yield, dry biomass yield, plant heights, leaves, and number of varieties.

Variety	N	Regression line	r	r^2	p
Alegria	10	Y = 6498.799 + 0.218X1–0.104X2 + 0.249X3	0.406	0.165	0.969
Amont	10	Y = 1734.297 + 0.086X1–0.522X2 + 0.685X3	0.608	0.369	0.891
Golden	10	Y = 7452.531 + 0.363X1–0.525X2 + 0.721X3	0.686	0.471	0.305
Mercado	10	Y = 3442.738 + 0.149X1–0.076X2 + 0.389X3	0.622	0.376	0.329
Hopy Red Dye	10	Y = 2065.164 + 0.397X1–0.4734X2 + 0.371X3	0.693	0.480	0.143
Opopeo	10	Y = 6939.331 + 0.462X1–0.53X2 + 0.334X3	0.797	0.636	0.718

Y—dry grain yield; X1—dry biomass yield; X2—plants heights; X3–leaves number

In the Mercado, Hop Red Dye, and Opopeo varieties, the dry biomass yield is moderately correlated with plant height and number of leaves, while in Amont and Golden, weak correlations are seen (Table 7). In Alegria, weak-to-moderate multiple correlations are observed between dry biomass yield, plant height, and number of leaves. In all studied varieties, according to regression lines, the plant height has a negative influence on dry biomass yield, while the number of leaves positively influences the yield; however, the multiple correlations are not significant.

For emphasizing the influence of morphological traits (plant height and number of leaves) on biomass grain yields, multiple correlations were calculated for each of the analyzed *Amaranthus* sp. varieties (Tables 7 and 8).

For emphasizing the influence of morphological traits (plant height and number of leaves) on biomass and grain yields, multiple correlations were calculated for each analyzed *Amaranthus* sp. varieties (Tables 7 and 8).

3.3. The Nutritional Content and Antioxidant Activity of Amaranth Varieties

According to the box plot diagram (Figure 5), moisture content ranges between 12.90 g/100 g (Alegria) and 11.20 g/100 g (Amont). No significant differences are observed between dry matter contents among all *Amaranthus* sp. varieties.

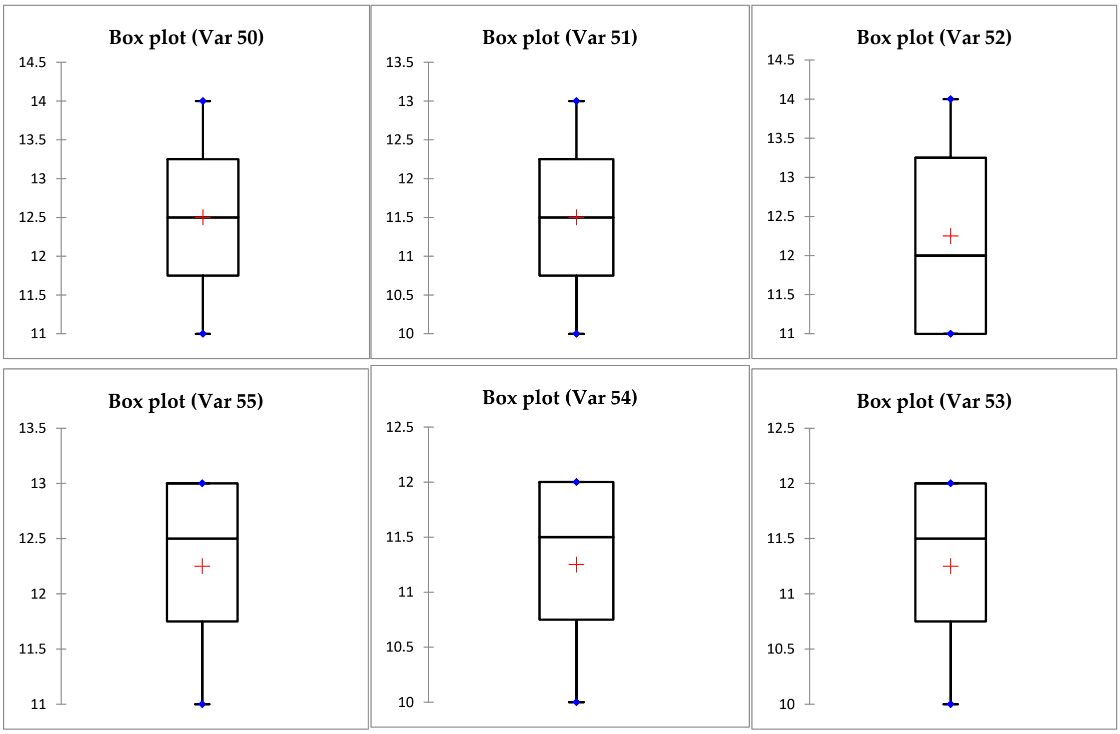

Figure 5. The box plot diagrams for the varieties' dry matter (g/100 g). Var 50—Alegria, Var 51—Amont, Var 52—Golden, Var 53—Mercado, Var 54—Hopi red Dye, Var 55—Opopeo.

According to our study, dry matter ranges between 87.10 g/100 g in Alegria and 88.8 g/100 g in Amont, while crude protein ranges between 18.20 g/100 g dry matter and 16.20 g/100 g dry matter (Table 9). No significant differences are observed between crude protein contents corresponding to five of the six studied varieties. The exception is crude protein content identified in Alegria, which significantly differs from the contents of the other varieties. The crude fiber content ranges between 20.40 g/100 g dry matter and 14.20 g/100 g dry matter. No significant differences are observed between crude fiber contents corresponding to Golden, Mercado, Hopi Red Dye, and Opopeo. Differences are reported concerning crude fiber content between Alegria, Amont, and the other studied varieties. The highest mean crude fat content corresponds to the Opopeo variety (10 g/100 g dry matter), and the lowest to Hopi Red Dye (6.80 g/100 g dry matter). The mean crude fat content from Amont, Golde, Mercado, and Hopi Red Dye differs significantly from those reported in Alegria and Opopeo. The mean crude ash ranges between 3 g/100 g dry matter (Alegria) and 2.20 g/100 g dry matter (Amont). No significant differences are seen between mean crude ash content corresponding to the studied *Amaranthus* sp. varieties. The highest mean content of nitrogen-free extracts of 57.20 g dry matter is reported in Amont, and the lowest of 52.10 g dry matter in Mercado. No significant differences are observed between mean nitrogen-free extracts contents corresponding to the Alegria, Golden, Hopi Red Dye, and Opopeo varieties. Differences are identified between mean nitrogen-free extracts contents corresponding to Amont and Mercado, on one hand, and between these means and those identified in the other four *Amaranthus* sp. varieties.

Table 9. The nutritional content of seven grains belonging to amaranth varieties (g/100 g dry matter).

Variety	Dry Matter	Crude Protein	Crude Fiber	Crude Fat	Crude Ash	Nitrogen-Free Extracts
Alegria	87.10 a ± 1.03	18.20 ± 0.58 ba	20.40 ± 0.54 a	9.00 ± 0.95 a	3.00 ± 0.38 a	54.30 ± 0.92 a
Amont	88.80 a ± 0.99	16.20 ± 0.93 ab	14.20 ± 0.45 b	7.00 ± 1.12 b	2.20 ± 0.36 a	57.20 ± 1.031 b
Golden	87.89 a ± 0.95	16.60 ± 0.41 b	16.60 ± 0.86 c	7.20 ± 1.16 b	2.40 ± 0.51 a	55.70 ± 0.86 a
Mercado	88.55 a ± 1.12	17.60 ± 0.51 ab	17.20 ± 0.66 c	7.00 ± 0.71 b	2.50 ± 0.40 a	52.10 ± 0.67 c
Hopi Red Dye	88.45 a ± 1.06	16.90 ± 0.40 b	17.40 ± 0.80 c	6.80 ± 0.49 b	2.70 ± 0.62 a	55.60 ± 0.86 a
Opopeo	87.39 a ± 0.93	17.00 ± 0.71 ab	17.80 ± 0.62 c	10.00 ± 0.83 a	2.90 ± 0.33 a	53.00 ± 1.02 ca

The differences between any two yield averages are significant, if their values are followed by letters, or groups of different letters.

The antioxidant activities of grains expressed as TPC differ in function of variety (Figure 6). Among the six *Amaranthus* sp. varieties, the highest means correspond to the Alegria and Mercado varieties, with values of 0.43 mg GAE/g and 0.41 mg GAE/g, respectively. The lowest mean of 0.19 g GAE/g corresponds to the Amont variety. No significant differences are observed between TPCs identified in the Golden and Hopi Red Dye varieties. Significant differences are reported between the other studied varieties on one hand, and between them and the Golden and Hopi Red Dye varieties on the other hand.

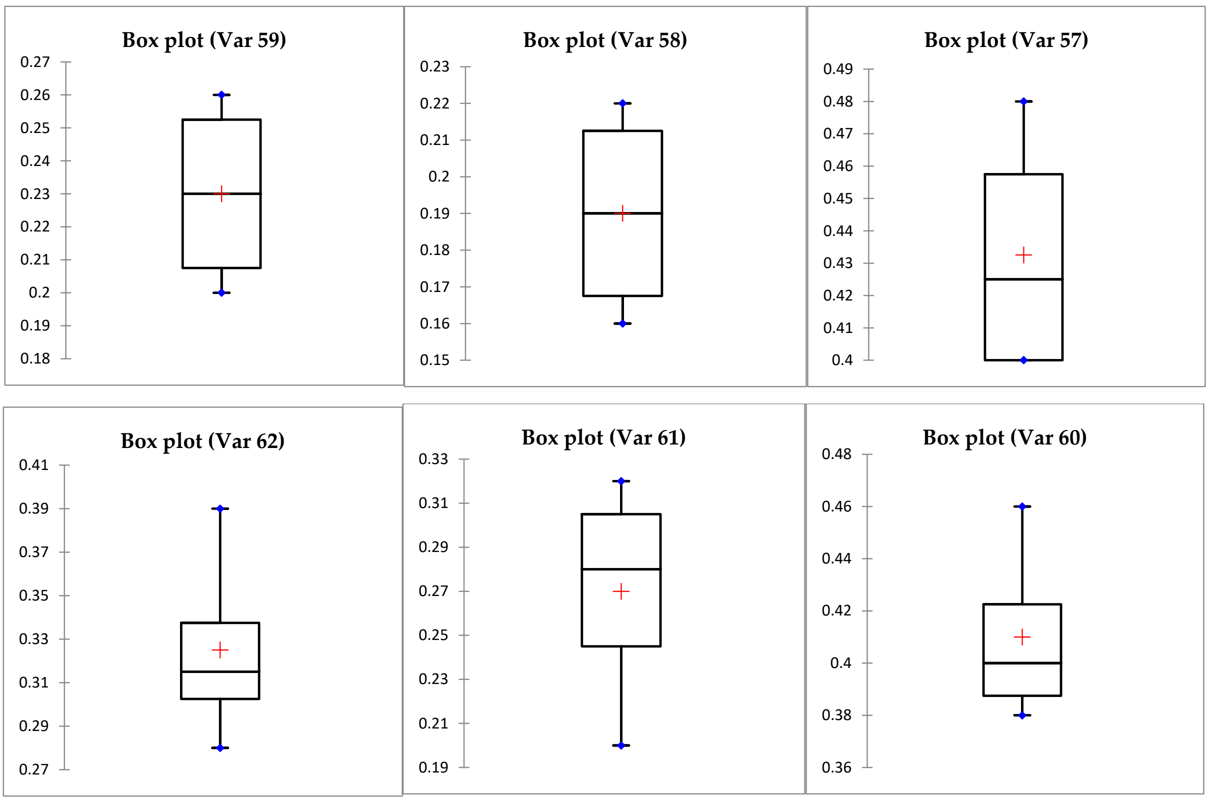

Figure 6. The box plot diagrams for varieties TPC (mg GAE/g). Var 57—Alegria, Var 58—Amont, Var 59—Golden, Var 60—Mercado, Var 61—Hopi red Dye, Var 62—Opopeo.

4. Discussion

We found differences between morphological traits represented by plant height and number of leaves. Additionally, productive traits such as biomass and seed yields differ significantly among amaranth varieties. Differences in morpho-productive traits were also obtained by Dehariya et al. (2019) when different levels of inputs were administered to an *A. tricolor* culture [34]. They report plant heights ranging between 27.23 and 45.68 cm, the number of leaves ranging between 9.73 and 13.53, and dry biomass yields between 1000.35 and 1807.90 kg/ha. These values are inferior to those obtained in our study (79.35–101.25 cm, 21.71–32, and 6603.20–10,068.06 kg dry biomass/ha, respectively). The reason may be the different varieties used in our trial, meaning *A. cruentus* and *A. hypochondriacus* versus *A. triclor*. Our results concerning plant height frame within a narrower range, and mean plant heights have lower values, compared to those reported by Baturaygil et al. (2021) in amaranth hybrids, which were between 109 and 253 cm [36], those by Bashyal et al. (2018) between 75.98 and 167.14 cm [37], and those by Génalis and Seguin (2008) in eight amaranth genotypes, between 143 and 168 cm [38]. The number of leaves (36.33–199.66) corresponding to results reported by Bashyal et al. (2018) is much higher [37] compared to values presented in our study. It is interesting to note that even though the above-mentioned studies present superior values of plant heights and number of leaves, the reported dry grain yields ranging between 724.96 and 1183.58 kg grains/ha [36], and 432 and 979 kg grains/ha [37], are inferior to those obtained in our study. Additionally, inferior results (780–1560 kg/ha) compared to those of our trial are reported by Gomes et al. (2023), in *A. cruentus* [39]. Similar results ranging between 2202 and 3006 kg/ha are reported by Gimplinger et al. (2024) in *A. hypochondriacus* [40]. These results suggest that besides specific varieties, pedo-climatical specific conditions may have an important role in the morpho-productive traits of amaranth. This finding suggests that *A. cruentus* and *A. hypochondriacus* have a high productive potential in cultivation conditions of our trial.

Like our findings, in a study performed on the *A. hypochondriacus* genotype, in Southern Italy, Pulvento et al. (2021) identified a strong correlation between dry grains and dry biomass [41]. The study of the relationships between morph-productive traits provides insights into the complex relationships between morphological traits and yield in different amaranth varieties. According to the multiple correlation intensities, the multiple regression analysis shows that plants height and leaves number influence in a lower extent the dry biomass yield, compared with their influence together with biomass yield on dry grains yield. The observed variations in correlations highlight the importance of considering specific varieties and their unique characteristics when optimizing cultivation practices for dry biomass and grain yields. The acknowledgment of weak or moderate correlations also suggests that other factors beyond plant height and leaf number may contribute to yield variations in these varieties.

The grouping of yields in PCA (Figure 4) is different from those resulting from dendrogram correspondent to cluster analysis (Figure 3), because PCA considers the yields' function of influence of principal factors. Differences are the result of high dry grain yields of Mercado and Golden varieties, to which correspond lower fresh grain yields. However, the results of both cluster analysis and PCA show the best suitability of the Alegria and Mercado varieties, and good suitability of the Golden, Hopy Red, and Opopeo varieties to specific environmental cultivation, in terms of dry grain yields.

Amaranth grains constitute a well-balanced reservoir of bioactive substances [40]. Our findings provide a detailed analysis of various nutritional components and TPC in the grains, underscoring the diversity in nutritional composition among different amaranth varieties. In our study, the moisture content has lower values and ranges in a narrower interval, 11.20–12.90 g/100 mg grains, compared to the results reported by Baturaygil et al. (2021) in amaranth hybrids (9–24%) [36]. For dry matter, slightly lower values (87.10–88.80%) are reported compared to those identified by Rosa et al. (2024) in *A. hypochondriacus*, and *A. cruentus*, ranging from 89.11 to 94.71 g/100 g [42]. The narrow range of dry matter content emphasized in all six amaranth varieties studied suggests a lack of diversity in this trait, but a similar tendency is reported by Oteri et al. (2021) in A. hypochondriacus between 89.80 and 89.60 g/100 g dry matter [43].

The protein content ranging between 16.20 and 18.20 g/100 g dry matter is similar to values reported by Malik et al. (2023) between 12.70 and 19.80 g/100 g dry matter [20], by Oteri et al. (2021) between 17.30 and 18.30 g/100 g dry matter [43], and by Mekonnen et al. (2018) in *A. caudatus* varieties (16.64%) [44], but higher compared to those obtained by Ma et al. (2024) of 12.24% [45], Rosa et al. (2024) of 14% [42], Haber et al. (2017) [9], 15.75%, and USDA (2010), 13.56% [1]. Thus, it can be seen that the protein content shows some variability and fits within the range reported by most studies, even though tends to be higher compared to some other studies; this adds nutritional value to the studied amaranth varieties.

Our findings also emphasize higher values of crude fiber ranging between 14.20 and 20.40 g/100 g dry matter, compared with those obtained by Malik et al. (2023) between 2.40 and 5.80 g/100 g dry matter [20], by Oteri et al. (2021) between 4.84 and 5.85 g/100 g dry matter [43], by Mekonnenet al. (2018) of 11.33% [44], Haber et al. (2017) of 4.2% [9], and USDA (2010) 6.7%% [1]. The high content of crude cellulose can be considered positive in terms of nutritional value and health benefits, if it is in a range that does not adversely affect the digestibility or quality of the finished products. Thus, fiber content identified in our study may be considered a challenge for food processors and consumers' acceptance.

The fat content quantified in our study ranging between 7.00 and 10.00 g/g dry matter is similar to the content reported by Haber et al. (2017) at 7.2% [9], and by Malik et al. (2023) between 1.70 and 10.30 g/100 g dry matter [20]. In the context of the entire nutritional profile of grains, the low-fat content of amaranth grains may contribute to a healthy diet, but also flexibility in food preparation.

The ash content reflects the presence of mineral elements. Similar results compared to those reported in our study ranging between 2.20 and 3.00 g/100 g dry matter, of 2.88%, and 2.40 g/100 g, are mentioned in the literature [1,43]. A mean of 3.3% ash content was observed in amaranth by Mekonnen et al. (2018) and Haber et al. (2017) [9,44], while Oteri et al. (2021) emphasized values between 3.26 and 3.54 g/100 g dry matter [43], and Malik et al. (2023) emphasized values between 2.20 and 3.50 g/100 g dry matter [20], which are slightly higher compared to our findings. We consider that the slightly lower ash content identified in our study may be influenced by the soil quality. The mineral content of amaranth varieties studied may have different significances on suitability of use as a functional food. A low crude ash content could mean, on one hand, that the plant does not provide significant levels of minerals, and on other hand, it could cope with low-ash foods requirements, which might be preferable for certain diets or for people who want to avoid certain minerals.

Studies suggest that red amaranth is notably abundant in polyphenols, particularly found in the seed coat [45–47]. The varieties with a superior red color index, such as A. cruentus and A. hypochondriacus, are significant reservoirs of phenolic and polyphenolic compounds, showing enhanced antioxidant activity. Our study shows a TPC in grains ranging from 19.23 to 43.17 mg GAE/100 g dry matter in A. cruentus, while other studies performed in the same variety emphasize similar TPC values of 30.48 mg GAE/100 g dry matter [48], or between 16 and 43 mg GAE/100 g dry matter [49]. Compared to TPC reported in our research in A. hypochondriacus ranging between 0.23 and 0.41 43 mg GAE/100 g dry matter, Oteri et al. (2021) and Gorinstein et al. (2007) report similar values ranging between 24 and 43 mg GAE/100 g dry matter [43,50], and 15.40 and 41.40 mg GAE/100 g dry matter [48]. The TPC content emphasized in studied amaranth varieties, similar with those reported by other research, contributes to its nutritional quality.

5. Conclusions

The research emphasizes differences concerning most of the analyzed morpho-productive traits within the studied *Amaranthus* sp. varieties, which fit within the amounts described in the literature. In varieties such as Mercado, Hop Red Dye, and Opopeo, a moderate correlation exists between dry biomass yield and both plant height and number of leaves, while weaker correlations are observed in the Amont and Golden varieties. The regression analysis indicates that plant height negatively impacts dry biomass yield, whereas the number of leaves positively influences yield. According to both cluster analysis and PCA, the Alegria, and Mercado varieties show the best suitability, while the Golden, Hopy Red, and Opopeo varieties show good suitability to specific pedoclimatic conditions of Someș meadow, Transylvania, in terms of dry grain yields.

Even though all six amaranth varieties studied show a narrow range of dry matter and ash content, concerning other nutritional components, differences are observed. The protein, fat, and TPC contents, which show some variability frame within the range reported by most studies, add nutritional value to the studied amaranth varieties. However, the high content of crude cellulose can be considered positive in terms of nutritional value because it might not align with preferences for certain food applications. Lower ash content and higher crude fiber content in the studied amaranth varieties could be considered as areas for further investigation and potential improvement. The lower crude ash content identified in our study compared to other studies could mean that amaranth varieties do not provide significant levels of minerals, but this could comply with low-ash food requirements.

In conclusion, while our research provides valuable insights into the performance and nutritional content of different amaranth varieties, there is a need for broader, more extensive studies across varied environments. Understanding the complex interactions between morphological traits and yield, as well as exploring the full spectrum of bioactive compounds, will be crucial for maximizing the potential of amaranth as a sustainable and nutritious crop.

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