

Phytopharmacological profile, nutritional value and amaranthine content of *Amaranthus* and their significance in medicine

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Abstract

The aim of this study was to determine the phytopharmacological properties and nutritional values in the protein and amino acid content of leaves and flowers in different species of the genus *Amaranthus* L., namely *A. molleros*, *A. caudatus*, *A. mantegazzianus*, and *A. cruentus*. The content of amaranthin, total content of low molecular weight soluble antioxidants (CCA), phenolic compounds, and ascorbic acid content in the mentioned species of amaranth were also determined. The studied six genotypes of amaranth belong to the collection of the Faculty of Agriculture, University of Belgrade. Amaranth is known to be an excellent food crop due to the high nutritional value of its seeds and leaves and it is excellent phyto-medicinal crop, as its inflorescences and leaves can be used as sources of antioxidants, and its seeds for producing gluten free health-safe products. In leaves, the lysine content ranged from 3.9% (*A. caudatus*) to 7.0% (*A. cruentus*; *A. molleros*), and in flowers from 4.2% (*A. caudatus*) to 7.4% (*A. cruentus* -G8) while the amaranth content varied (1.2-2.2%), antioxidants (CCA 1.6-3.5%), and ascorbic acid content (150-200%). Amaranth has the ability to improve the functionality of the immune system, enabling an outstanding balance of amino acid composition, as well as the ratio of lysine to arginine. Antioxidants, amaranth and ascorbic acid content significantly contributes to the ability to improve the functionality of the human immune system. Duodenal peptic ulcer and chronic gastritis caused by *Helicobacter pylori* can be treated with amaranth oil.

Keywords: *Amaranth*; amaranthine; amino acid; nutritional value and use in medicine; phytopharmacological profile

Introduction

Amaranth is a pseudo-cereal crop that are primarily utilized as green vegetables and grains for food. *Amaranthus* has attracted the attention of both scientific and professional communities, including pharmaceutical, food, confectionery, cosmetic, and animal feed industries. Its significance arises from its biological properties, rich phytochemical composition, and a wide range of pharmacological activities. Amaranthus is a pseudocereal with a dual nature, combining characteristics of food and health-promoting products. The genus *Amaranthus* L. belongs to the order Caryophyllales, family Amaranthaceae, subfamily Amaranthoideae. Three species of amaranth have been grown entirely for grains: *A. cruentus* (red amaranth), *A. caudatus* (love-lies-bleeding), and *A. hypochondriacus* (Prince-of-Wales feather) (Cheng, 2018). It comprises branched annual herbs with around 70 different species, of which 17 are edible. The National Botanical Research Institute of India (NBRI) has created one of the best collections of amaranth 'germplasm' in the world, consisting of nearly 400 specimens related to 20 species, almost half of which belong to grain species. The center of origin of this crop is Central America and it was a major crop in the civilizations of the Aztecs, Maya, and Incas. It is currently widely cultivated and consumed across India, Nepal, China, Indonesia, Malaysia, the Philippines, Mexico, and in countries of South and East Africa. Amaranthus can also be used for medicinal purposes, hence recent research is directed in that direction. Scientific interest in Amaranthus and its health benefits has significantly increased in the last decade of the 20th century, with various reviews presenting the nutritional properties of Amaranthus, its composition, antioxidant properties, application, and industrial processing into finished products (Glamočlija *et al.*, 2015). *A. caudatus* grain can be dried, milled and used for human nutrition in the form of whole-meal amaranth flour, crackers, brown bread without gluten, biscuits, cookies, (Mekonnen *et al.*, 2018). Medicinal plants like Amaranthus have continued to play a crucial role in meeting primary healthcare needs globally, especially during sudden outbreaks of deadly diseases like COVID-19. New technologies, including the screening of chemical libraries obtained from plants and the application of computer techniques, aided by computer-aided drug design (CADD), are increasingly being applied in rapidly selecting compounds for screening candidates for the rapid drug discovery process, especially during emergencies such as the COVID-19 pandemic. In silico analysis reduces the research timeline for identifying "generic formulas" and analyzing their suitability in combating pathogenic diseases, thus shortening the time frame for the creation of innovative drugs. Numerous pharmacological studies have shown that certain bioactive compounds isolated from Amaranthus exhibit hepatoprotective, radioprotective, anti-inflammatory, antipyretic, antihepatotoxic, antidiabetic, antihyperlipidemic, spermatogenic, antiproliferative, antifungal, and other beneficial medical effects. Amaranthus leaves contain flavonoids such as quercetin, trifolin, and rutin (3%) (Stevanović *et al.*, 2023a; 2023b). The nutritional value of amaranth grains indicates that it is highly nutritious and a good source of anthocyanins and polyphenols. The grain has a high protein content, a well-balanced amino acid profile with 18 essential amino acids, and a very high level of lysine which is unique compared to other cereals. It is rich in starch, oil, fiber, vitamins (A, K, B6, C, E, and B), and minerals such as calcium, iron, etc. It is gluten-free, and its high content of quality proteins and unsaturated fatty acids is one of its advantages as a dietary supplement. Amaranth seeds are also carriers of valuable fibers and an alternative natural source of squalene (triterpene), which is a superior antioxidant known for its wide biological efficacy against cancer, hypercholesterolemia, and as a cardio protectant (Stevanović *et al.*, 2023a). Therapeutically, the roots are boiled with honey as a laxative for infants (Paredes-Lopez and Hernández-López 1992). The traditional use of medicinal herbs while respecting the principles of modern science has proven the presence of significant compounds in medicinal herbs with high biological activity. The goal of improving this production, apart from increasing farmers' profit, is the development of food products that have a positive effect on human health, prevent and reduce the risk of disease (Popović *et al.*, 2013; 2021; 2022a; 2022b; Petrović *et al.*, 2021; 2022; Lakić *et al.*, 2022; Nožinić *et al.*, 2022; Filipović *et al.*, 2021; 2023; Burić *et al.*, 2023; Vasileva *et al.*, 2023; Simić *et al.*, 2023; 2024). Because of all the above, the aim of this study was to examine phytopharmacological

properties and nutritional values, protein and amino acid content of leaves and flowers in different species of the genus *Amaranthus* L., namely *A. molleros*, *A. caudatus*, *A. mantegazzianus*, and *A. cruentus*.

Materials and Methods

Six genotypes of amaranth belonging to the species *A. molleros*, *A. caudatus*, *A. mantegazzianus*, and *A. cruentus* were examined. The lines of these species are grown annually in the experimental plot of the ZZ “Morava” nursery - Donja Trnava and represent a collection of the Department of Plant Genetics and Breeding of the Faculty of Agriculture, University of Belgrade. Samples for biochemical studies (leaves and inflorescences) were harvested during the flowering stage of plants in 2019 and 2020 (Stevanović, 2022), Pictures 1a-b. The protein content was determined using the Kjeldahl method of nitrogen analysis ($N \times 6.25$). The amino acid profile of leaves and flowers of amaranth was investigated in 6 genotypes belonging to the following species: *A. molleros* (G1), *A. caudatus* (G2 and G4), *A. mantegazzianus* (G3) and *A. cruentus* (G5 and G6), collection of the Faculty of Agriculture, University of Belgrade, Table 1, Figure 1a -1b.

Table 1. Introduced varieties/lines of amaranth

| No | Species | Genotype | Line/Variety |
|----|--------------------------|----------|--------------|
| 1. | <i>A. molleros</i> | G 1 | 18 |
| 2. | <i>A. caudatus</i> | G 2 | 45/1 |
| 3. | <i>A. mantegazzianus</i> | G 3 | 14 |
| 4. | <i>A. caudatus</i> | G 4 | 45/4 |
| 5. | <i>A. cruentus</i> | G 5 | 2 |
| 6. | <i>A. cruentus</i> | G 6 | 16 |



a)



b)

Picture 1. a) Amaranth planth and **b)** Amaranth seed

In addition to the total protein content of the leaf and flower, the content of 18 essential amino acids in the protein hydrolysate (Mol %) was also determined. Analyses of the amino acid profile of amaranth leaves and flowers were conducted using ion exchange chromatography, employing an automatic amino acid analyzer Biochrom 30+ (Biochrom, Cambridge, UK), following the method by Spackman *et al.* (1958). The content of amarantin in the water extract was determined using a molar extraction coefficient of 5.6×10^4 . The spectral color characteristics were studied by recording the absorption spectrum in the range of 250 - 600 nm using an SF-46 spectrophotometer. The total content of antioxidants was determined by the amperometric method (Subhasree *et al.*, 2009), and the quantity of phenolic compounds was determined according to McDonald *et al.* (2021).

Statistical analysis

The indicators of variability for the sought characteristics were with the descriptive statistics, the mean value (\bar{x}), standard deviation (SD), and coefficient of variation (CV, %), calculated using the equations provided in Table 2.

Table 2. Formulas for processing data

| Sample mean value | Standard deviation | Coefficient of variance |
|-------------------------------|---|-------------------------------------|
| $\bar{x} = \frac{\sum xi}{N}$ | $S = \sqrt{\frac{\sum (x - \bar{x})^2}{N - 1}}$ | $Cv = \frac{S \times 100}{\bar{x}}$ |

Results and Discussion*Nutritional value of amaranth seeds and leaves*

The average amaranth protein content of seed (PCS) was 15.4% and varied 14.6% (G4-*A. caudatus*) to 16.6% (G5-*A. cruentus*) and the coefficient of variation ranged from 0.3% (G1-*A. molleros*) to 1.3% (G3-*A. mantegazzianus*), Table 3, Figure 2. Analysis of variance showed that the analyzed species are very significant differences in PCS, Table 3. Average percentage of PCS of *A. cruentus* is 17.8% and *A. caudatus* 14.9% (Hadživuković, 1991).

Table 3. Average values (̄) for protein, ash, and oil (%) content in seeds and leaves of Amaranthus species and coefficients of variation (CV) and standard deviation (SD)

| Parameter | | G1- <i>A. molleros</i> | G2- <i>A. caudatus</i> | G3- <i>A. mante-gazzianus</i> | G4- <i>A. caudatus</i> | G5- <i>A. cruentus</i> | G6- <i>A. cruentus</i> | \bar{x} | SD |
|---------------------------|-----------|------------------------|------------------------|-------------------------------|------------------------|------------------------|------------------------|-----------|-----|
| Protein content of seed | \bar{x} | 15.0 | 14.9 | 15.1 | 14.6 | 16.6 | 16.4 | 15.4 | 0.9 |
| | CV | 0.3 | 0.7 | 1.3 | 0.6 | 0.7 | 0.6 | 0.7 | - |
| Protein content of leaves | \bar{x} | 16.0 | 20.1 | 17.0 | 19.5 | 18.0 | 17.9 | 18 | 1.5 |
| | CV | 0.4 | 0.9 | 0.4 | 0.7 | 0.5 | 0.6 | 0.6 | - |
| Ash content of seeds | \bar{x} | 2.7 | 2.3 | 2.6 | 2.2 | 2.4 | 2.3 | 2.4 | 0.2 |
| | CV | 2.6 | 8.2 | 16.2 | 8.5 | 10.5 | 9.0 | 9.2 | - |
| Ash content of leaves | \bar{x} | 17.7 | 16.3 | 18.8 | 16.1 | 18.3 | 17.9 | 17.5 | 1.1 |
| | CV | 0.6 | 2.2 | 0.7 | 1.8 | 0.8 | 0.7 | 1.1 | - |
| Oil content of seeds | \bar{x} | 6.2 | 5.8 | 5.6 | 5.9 | 6.1 | 6.0 | 5.9 | 0.2 |
| | CV | 1.5 | 3.6 | 7.2 | 3.5 | 3.4 | 3.3 | 3.8 | - |

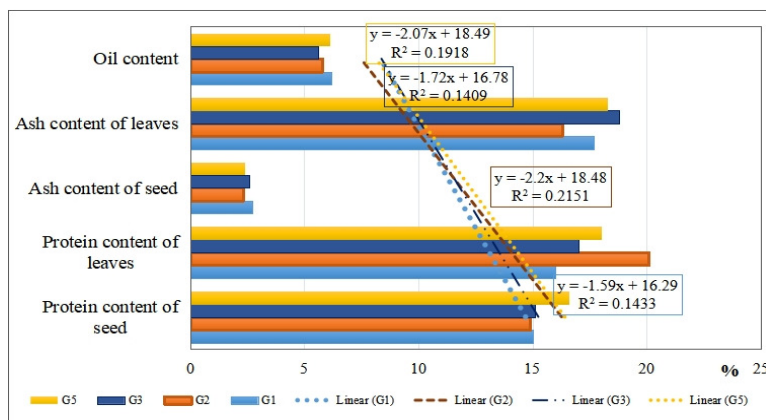


Figure 2. *Amaranthus* species protein and ash content of seeds and leaves, and oil content in seed G1-*A. molleros*; G2- *A. caudatus*; G3- *A. mantegazzianus* and G5- *A. cruentus*

Protein content of amaranth leaves - PCL in addition to the PCS is the most important qualitative character of *Amaranthus*. Average PCL was 18.1% and varied from 16.0% (G1-*A. molleros*) to 20.1% (G2-*A. caudatus*), Table 3, Figure 3. Indicators of variability within the analyzed species varied in a very small range of 0.4% (G1- *A. mantegazzianus*) to 0.9% (G2- *A. caudatus*), while average of coefficient of variation is 0.6% (Table 3).

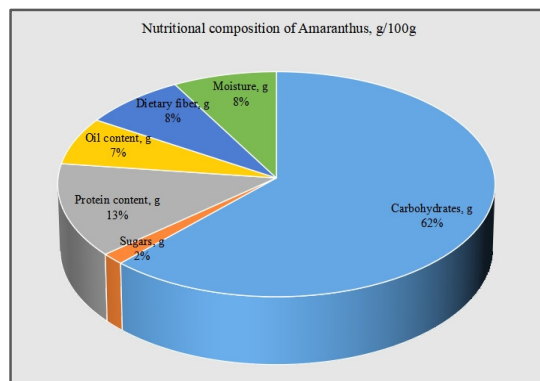


Figure 3. Nutritional value of amaranth seeds (g per 100 g)

The influence of the type is highly significant for the PCL of amaranth (Table 3). Protein contents of Amaranth seeds were reported as 9.2% in *A. blitoides*, and 15% in *A. muricatus* (Juan *et al.*, 2007). PCL of Amaranth species have been reported differently such as in Amaranthus hybrids was 17.92% (Akubugwo *et al.*, 2007) and in *Amaranthus cruentus* was 23.0% (Fasuyi *et al.*, 2007; 2008). The nutritional value of the amaranths seeds are composed of 14.1% of protein content, 7.2% of oil content, 65.1 g of carbohydrates, 8.4% of dietary fiber, Table 4, Figure 3.

The protein contained in amaranth is of high quality due to its good balance and high content of essential amino acids. The essential amino acids in amaranth grain are ideal according to the World Health Organization (WHO) and Food and Agriculture Organization of the United Nations (FAO). The amount of lysine and tryptophan present in amaranth grain are relatively higher than those found in wheat, rice, and maize grains, but it is deficient in leucine (Soriano-García and Aguirre-Díaz, 2019). Amaranth are rich in minerals (Ca-158.5 mg; Fe-7.7 mg; Mg-249.1 mg; Mn-3.3 mg; P-558.1 mg; K-509.1 mg; Na-4.1 mg; Zn-2.9 mg; Se-18.7

mcg and Cu-0.6 mg) and vitamins (C-4.2 mg; B2-0.2 mg; B12-69.8 mg; B9-82.2 mg; B3-0.9 mg; B5-1.5 mg; B6-0.6 mg; B1-0.1 mg; A-2.1 IU, E-1.2 mg), Table 4.

Amaranth is rich in essential amino acids and showed a near-optimal protein composition that is similar to those found in cow's milk (Bekkering and Tian, 2019). These underutilized grains are also safe for celiac disease patients to consume due to the lack of gluten content. Despite being very nutritious, these grains have limited bioavailability due to the presence of anti-nutritional ingredients like phytic acid and saponins that bind with nutrients and render them unavailable to our body (Repo-Carrasco *et al.*, 2003).

Table 4. Nutritional value of amaranth seeds (g per 100 g)

| Parameters | Amaranth g/100 g | Energy and Vitamins | Amaranth, g/100 g |
|--------------------|---------------------|--|----------------------|
| Carbohydrates, g | 65.1 | Energy, kcal | 430 |
| Sugars content, g | 1.7 | Energy, kJ | 1604 |
| Protein content, g | 14.1 | Vitamins | |
| Oil content, g | 7.2 | Ascorbic acid, Vitamin C, mg | 4.2 |
| Dietary fiber, g | 8.4 | Riboflavin, Vitamin B2, mg | 0.2 |
| Moisture, g | 8.5 | Choline, Vitamin B12, mg | 69.8 |
| Minerals | | Folate, Vitamin B9, mcg | 82.2 |
| Calcium, Ca, mg | 158.5 | Betaine, Trimetilglicin, mg | 67.6 |
| Iron, Fe, mg | 7.7 | Retinol, Vitamin A 2IU, IU | 2.1 |
| Magnesium, Mg, mg | 249.1 | Niacin, Vitamin B3, mg | 0.9 |
| Manganese, Mn, mg | 3.33 | Pantothenic acid, Vitamin B5, mg | 1.5 |
| Phosphorus, P, mg | 558.1 | Piridoksin, Vitamin B6, mg | 0.6 |
| Potassium, K, mg | 509.1 | Vitamin E 1.19 mg (alpha-tocopherol), mg | 1.2 |
| Sodium, Na, mg | 4.1 | Vitamin E 0.96 mg (beta-tocopherol), mg | 1.0 |
| Zinc, Zn, mg | 2.9 | Vitamin E 0.69 mg (delta-tocopherol), mg | 0.7 |
| Selenium, Se, mcg | 18.7 | Thiamine, Vitamin B1, mg | 0.1 |
| Copper, Cu, mg | 0.6 | Lutein, Carotenoid, mcg | 28.1 |

Amino acids content in amaranth leaves and flowers

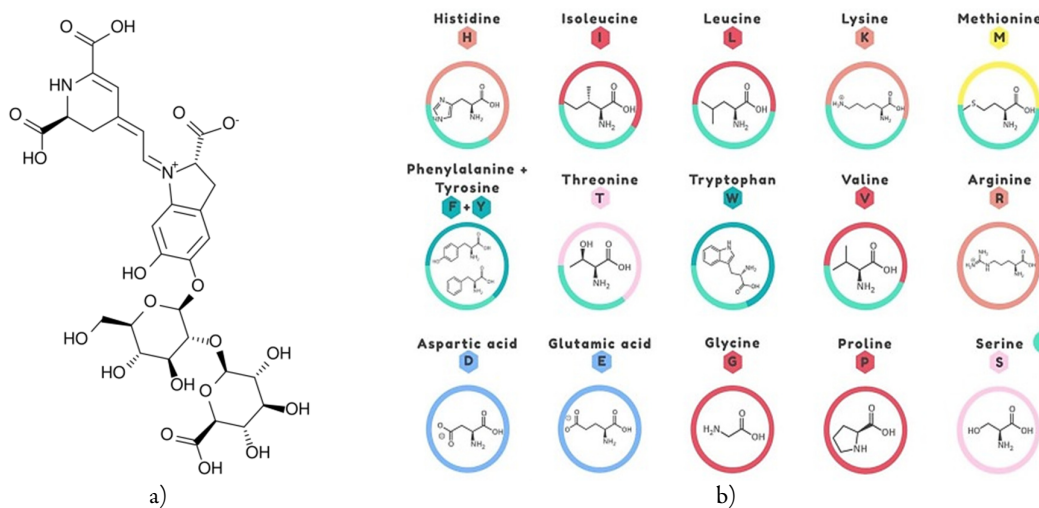
The obtained results for lysine and methionine content are highly significant, including the values for arginine, Table 5, Figures 4a-3b. In amaranth leaves, the lysine content ranged from 3.8 g/100 g of protein (*A. caudatus*-genotype 2) to 7.3 g/100 g of protein (*A. cruentus*-genotype 5) and (*A. molleros*-genotype 1). In amaranth flowers, the lysine content ranged from 4.2 g/100 g of protein (*A. caudatus*-genotype 2) to 7.4 g/100 g of protein (*A. cruentus*-genotype 6), Table 5. The methionine content ranged from 3.2 g/100 g of protein (*A. caudatus*-genotype 2) to 7.5 g/100 g of protein (*A. mantegazzianus*-genotype 3) in leaves, and 2.9 g/100 g of protein (*A. caudatus*-genotype 2) to 6.7 g/100 g of protein (*A. mantegazzianus*-genotype 3) in amaranth flowers, Table 5.

The arginine content ranged from 7.9 g/100 g of protein (*A. caudatus* - genotype 4) to 11.6 g/100 g of protein (*A. caudatus*-genotype 2) in leaves, and from 8.1 g/100 g of protein (*A. cruentus*-genotype 6) to 10.7 g/100 g of protein (*A. caudatus*-genotype 2) in amaranth flowers, Table 5.

Table 5. Amino acids content of *Amaranthus* species

| Amino acid, g/100 g protein | <i>A. molleros</i> G 1 | | <i>A. caudatus</i> G 2 | | <i>A. mantegazzianum</i> , G 3 | | <i>A. caudatus</i> G 4 | | <i>A. cruentus</i> G 5 | | <i>A. cruentus</i> G 6 | |
|--------------------------------|---------------------------|------|---------------------------|------|--------------------------------|------|---------------------------|------|---------------------------|------|---------------------------|------|
| | L* | F | L* | F | L* | F | L* | F | L* | F | L* | F |
| Glycine | 9.3 | 8.6 | 9.7 | 8.9 | 9.1 | 7.9 | 7.4 | 6.8 | 9.3 | 8.9 | 10.7 | 10.5 |
| Alanine | 5.2 | 4.8 | 6.8 | 5.8 | 6.5 | 6.7 | 6.2 | 6.0 | 6.6 | 6.2 | 6.6 | 6.4 |
| Leucine | 5.5 | 4.9 | 6.4 | 7.8 | 4.5 | 6.1 | 7.5 | 6.8 | 5.6 | 5.2 | 4.9 | 4.5 |
| Isoleucine | 4.1 | 4.5 | 4.2 | 4.3 | 2.7 | 2.9 | 5.2 | 5.3 | 3.9 | 3.5 | 3.3 | 3.5 |
| Valine | 3.9 | 4.5 | 6.4 | 5.9 | 4.6 | 4.7 | 5.0 | 4.5 | 4.8 | 5.0 | 3.9 | 4.2 |
| Serine | 6.3 | 6.7 | 8.3 | 7.8 | 4.9 | 4.9 | 6.4 | 7.5 | 5.1 | 5.3 | 5.8 | 6.2 |
| Aspartic acid | 6.3 | 6.5 | 9.5 | 9.1 | 7.6 | 7.9 | 10.3 | 9.5 | 9.4 | 8.0 | 8.2 | 7.9 |
| Glutamic acid | 17.8 | 16.8 | 17.3 | 19.1 | 17.4 | 17.5 | 16.4 | 20.9 | 17.2 | 16.7 | 16.8 | 17.6 |
| Cysteine | 4.4 | 4.6 | 4.3 | 4.4 | 2.7 | 3.1 | 4.8 | 4.4 | 4.1 | 3.7 | 3.9 | 4.5 |
| Methionine | 4.5 | 3.9 | 3.2 | 2.9 | 7.5 | 6.7 | 5.1 | 4.9 | 4.6 | 3.5 | 4.1 | 4.5 |
| Lysine | 7.3 | 6.7 | 3.8 | 4.2 | 5.8 | 6.1 | 6.7 | 7.2 | 7.3 | 6.6 | 6.7 | 7.4 |
| Arginine | 9.3 | 8.7 | 11.6 | 10.7 | 8.4 | 9.5 | 7.9 | 8.3 | 9.7 | 9.4 | 8.5 | 8.1 |
| Tyrosine | 4.5 | 3.8 | 4.3 | 4.4 | 3.3 | 4.2 | 2.9 | 3.1 | 5.1 | 5.4 | 3.7 | 3.4 |
| Tryptophan | 0.6 | 1.3 | 0.4 | 0.8 | 0.7 | - | 1.0 | - | 1.2 | 0.8 | 0.4 | 0.9 |
| Histidine | 2.2 | 1.9 | 3.6 | 3.8 | 3.1 | 3.2 | 3.1 | 2.7 | 2.5 | 2.3 | 3.2 | 3.2 |
| Phenylalanine | 31 | 4.9 | 3.8 | 5.0 | 4.5 | 3.7 | 3.4 | 5.1 | 3.2 | 5.3 | 4.7 | 4.3 |
| Threonine | 2.5 | 2.9 | 4.1 | 3.8 | 3.6 | 3.9 | 2.9 | 3.1 | 3.9 | 4.1 | 3.1 | 3.3 |
| Proline | 4.2 | 3.9 | 5.3 | 5.4 | 4.7 | 4.2 | 4.6 | 4.2 | 4.1 | 3.8 | 3.7 | 3.9 |

* L- Leaves; F- Flowers; G1-G6 - Genotypes 1-6

**Figure 4.** Amaranthine chemical structure, a), and amino acids content of *Amaranthus*, b)

The protein content in amaranth leaves was rich in all essential amino acids compared to FAO/WHO (1973) requirements, as their content was higher than that in the reference protein. The FAO listed amaranth as one of the most future promising crops for feeding the world's population. Among green leafy vegetables and cereals, *Amaranthus* species are recognized as a storehouse for essential vitamins like vitamin B6, C, folate, as well as carotene which is a precursor to vitamin A (Mekonnen *et al.*, 2018). Amaranth contains remarkably higher levels of magnesium, calcium, sodium, zinc and iron than quinoa (Krkoskova and Mrazova, 2005).

Amaranth is a gluten-free pseudo-cereal that might be included in gluten-free recipe formulations, thus providing a different food composition for celiac patients other than wheat and gluten-rich cereals (Shyam and Raghuvanshi, 2015). Only the content of the amino acid tryptophan was at the level of the reference protein. Compared to other staple cereals like: maize, wheat, and sorghum, amaranth has a higher protein level (14.0–

15.5%), a lower fat content (7.5%), a higher carbohydrate content (60–68%), and less ash content (2.5–3.1%), (Grobelnik *et al.*, 2009).

Most cereal grains generally lack the essential amino acid lysine and are rich in valine, leucine, and isoleucine while amaranth is high in lysine (5.2–6.1 g/100 g protein) and therefore has a well-balanced amino acid composition and meets the needs of the human diet for the majority of the essential amino acids namely, alanine, valine, leucine, arginine, phenylalanine, methionine, tryptophan, isoleucine, and serine which suggests that amaranth is a pseudo cereal which can be used as a substitute to nutrient cereal (Rastogi and Shukla, 2013). Amaranth protein contains a comparatively high amount of sulfur-containing amino acids, which are typically scarce in pulse crops (Grobelnik *et al.*, 2009).

It is known that betalains, red-purple amaranthine, new betaxanthin, methyl derivatives of arginine betaxanthin, and betalamic acid have been discovered in the leaves of *A. tricolor* (Kumar *et al.*, 2009). In an exclusive study, Jhade *et al.* (2011) reported alkaloids, glycosides, terpenes, and sugars as the main phytochemicals in the root of *A. spinosus*.

Patil *et al.* (2013) indicates a lack of similar studies on rutin and quercetin derived from *Amaranthus*, highlighting the need for clinical research in this area. These compounds possess diverse properties and are considered to be the main compounds responsible for the beneficial health effects of *Amaranthus* spp. Relevant benefit obtained of amaranth is included in diet is that due to its high amount of manganese, it represents a good option for regulating sugar levels. In the organism manganese helps during gluconeogenesis, it is possible to protect against diet-induced diabetes (Lee *et al.*, 2013).

Manganese is needed in adequate levels to avoid abnormalities in cholesterol levels, skin and bone health (Rucker *et al.*, 2010), and renal health (Koh *et al.*, 2014). It has been shown that the influence of dietary therapy which uses sunflower and amaranth oils on parameters of immune reactivity in patients with diabetes mellitus type 2 (Miroshnichenko *et al.*, 2009), and the activation of aerobic metabolism by amaranth oil improve heart rate variability both in athletes and patients with diabetes (Yelisseyeva *et al.*, 2012).

Amaranthine content, soluble antioxidants and total phenolic compounds

Amaranthine is a disaccharide derivative where betanidin is linked to a beta-D-glucuronosyl-(1->2)-beta-D-glucosyl group at position 5, Figure 4. It serves as a plant metabolite and biological pigment. It is a disaccharide derivative, olefinic compound, tetrahydropyridine, and member of the indole family. Functionally, it is related to betanidin. The obtained results for the amaranthine content, soluble antioxidants, and total phenolic compounds are very significant, with values for amaranthine ranging 1.2 -1.9 mg/g in the leaf and from 1.3 to 2.2 mg/g in the flower, Table 6, Figure 5.

Table 6. Amaranthine content, total content of soluble low molecular weight antioxidants (CCA), phenolic compounds (Σ PC) in ACB, and ascorbic acid (AA) content in amaranth

| Parameter | Amaranthine content, mg/g | CCA, mg | Σ PC% | AA, % |
|-----------|---------------------------|---------|--------------|---------|
| Leaves | 1.2-1.9 | 1.6-3.5 | 4.9-5.6 | 150-185 |
| Flowers | 1.3-2.2 | 1.8-3.1 | 5.2-5.9 | 165-200 |

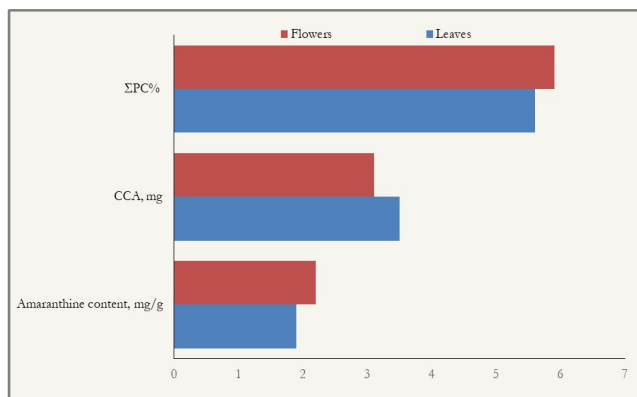


Figure 5. Maximum value of AC - amaranthine content, PC- phenolic compounds and CCA- soluble low molecular weight antioxidants of *Amaranthus*

In amaranth leaves, the content of soluble antioxidants (CCA) ranged from 1.6 mg to 3.5 mg, while in amaranth flowers, the values for soluble antioxidants ranged from 1.8 mg to 3.1 mg (CCA). The content of total phenolic compounds ranged from 4.9% (ACB) to 5.6% (ACB) in the leaf, and from 5.2% (ACB) to 5.9% (ACB) in the flowers of amaranth. Besides the leaves, amaranth flowers are also rich in ascorbic acid (AA, mg %), see Table 6.

The high nutritional quality of amaranth seed protein is one of the main factors which is why its demand and consumption is growing year by year. Amaranth seeds have a protein content of 14–18%, which is superior to that of most cereals (10% dry basis). Its proteins have an exceptional essential amino acid pattern, being relatively rich in lysine, tryptophan, and methionine. Amaranth seeds contain adequate levels of important micronutrients such as minerals and vitamins and significant amounts of other bioactive components such as saponins, squalene and phenolic compounds (Nsimba *et al.*, 2008; de la Rosa *et al.*, 2008). An important role is played by phenolic compounds and their antioxidant activity because epidemiological studies linking the consumption of diets rich in natural antioxidants with de-creased risk of diseases associated with oxidative stress, such as cancer and cardiovascular disease (Thaipong *et al.*, 2006).

Carrasco and Encina (2008) reported total phenolic content for methanol extracts from six varieties of *Amaranthus caudatus* ranging from 0.19 to 0.30 mg GAE/g dw. Czerwinski *et al.* (2004) reported values of 0.149 and 0.147 mg GAE/g of flours from two varieties of *Amaranthus hypochondriacus*. Carrasco and Encina (2008) reported antioxidant activity values in the range 0.56–0.66 mg TE/g dw for hydrophilic extracts (acetone: water: acetic acid) of six varieties of *A. caudatus*.

Health benefits of Amaranthus L.

Phenolic acids (Vanillic acid) have anti-cancer, anti-obesity, anti-diabetic, anti-bacterial, anti-inflammatory, and antioxidant properties (Kaur *et al.*, 2022) and Gallic acid have anti-inflammatory, anti-oxidative, anti-tumor, anti-bacterial, anti-diabetes, anti-obesity, anti-microbial, and anti-myocardial ischemia properties (Bai *et al.*, 2021; Kaur *et al.*, 2022).

The diverse health benefits arising from the consumption of amaranth grains and leaves are the subject of comprehensive interest in the fields of nutrition and health sciences. Amaranth stands out as a rich source of lysine, an essential amino acid that plays a key role in protein synthesis and maintaining the body's metabolic balance. Its nutritional value stems from the high content of minerals such as magnesium, iron, phosphorus, potassium, as well as vitamins C and E, which are known for their ability to neutralize free radicals and reduce oxidative stress, a key factor in the pathophysiology of various forms of degenerative diseases, including cancerous processes. The antioxidant properties of copper and manganese present in amaranth further

contribute to cell protection from oxidative damage (House *et al.*, 2020; Baraniak and Kania-Dobrowolska, 2022).

Phytoconstituents, macronutrients, minerals, and dietary fiber there is more in *Amaranthus spp.* than most traditional cereals. *Amaranthus spp.* offers excellent antioxidant activity compared to cereals. A special feature of amaranth is its hydrolysates and bioactive peptides with superior antioxidant activity compared to the parent isolate. Findings suggest that the combined action of germination and enzymatic hydrolysis could increase the antioxidant capacity of the amaranth plant. Nevertheless, not many *in vivo* experiments have been carried out hitherto, so the precise effect on the human body is not understood and research should continue (Park *et al.*, 2020). Bioactive components present in amaranth, amaranthine, gallic acid, rutin and quercetin have: antioxidant, antimicrobial, and cytotoxic properties (Amaranthine, Roriz *et al.*, 2021), anti-inflammatory, anti-oxidative, anti-tumor, anti-bacterial, anti-diabetes, anti-obesity, anti-microbial, and anti-myocardial ischemia properties (Gallic acid), anticancer, antioxidant, anti-diabetic, anti-inflammatory, antibacterial, antifungal, neuroprotective, cardioprotective, hepatoprotective, nephroprotective, and haematoprotective properties (rutin) and antioxidant, antifungal, anti-carcinogenic, anti-inflammatory, hepatoprotective, and cytotoxic activity (quercetin), (Prasad and Prasad, 2019), Figure 6a-d.

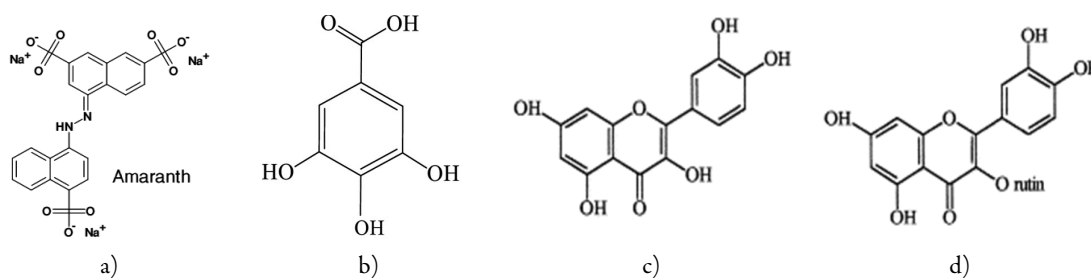


Figure 6. Amaranth, a, gallic acid, b, rutin, c, quercetin, d.

Amaranth are processed using various processing techniques including germination, extrusion, fermentation, and cooking to enhance their organoleptic and nutritional attributes. Regarding amaranth leaves, their nutritional value is also noteworthy, as they are rich in carbohydrates, proteins, vitamins (K, A, B6, C), and minerals (manganese, iron, copper, calcium, magnesium, potassium, phosphorus). These nutrients have a wide range of physiological functions, including support for the immune system, regulation of metabolic processes, and maintenance of bone tissue and cardiovascular system health, Figure 7.

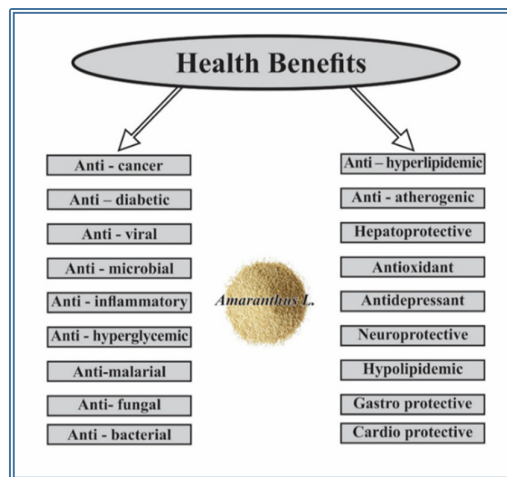


Figure 7. Health benefit of amaranth seeds

Phytosterols in amaranth stand out for their role in modulating lipid metabolism, especially in regulating cholesterol levels, which contributes to reducing the risk of cardiovascular diseases. The significant content of dietary fiber in amaranth positively affects the function of the gastrointestinal tract, providing support to digestive function and reducing the risk of gastrointestinal diseases. The absence of gluten in amaranth makes it a suitable choice for individuals who are gluten intolerant or suffer from celiac disease. Regulation of insulin and appetite levels, as well as contributions to bone health and the hematopoietic system, are further confirmed as beneficial effects of consuming amaranth (Glamočlija *et al.*, 2015).

Amaranthus viridis, is traditionally used for treatment of constipation, inflammation, eczema, bronchitis, anemia, leprosy. Flavonoids, rutin and quercetin possess many biochemical effects like inhibition of enzymes, regulatory role on different hormones and pharmacological activities like antimicrobial, antioxidant, and anticancer, antihepatotoxic, protection of cardio vascular system (Kumar *et al.*, 2009), Figure 7.

Amaranth represents a valuable resource in health promotion and disease prevention, and its consumption is an important factor in improving nutrition and overall health status. It has been documented that the seeds of *A. caudatus* and *A. paniculatus* possess antioxidant potential (Kumar *et al.*, 2009). Silva-Sánchez *et al.* (2008) reported the presence of a lunasin-like peptide (11.1 mg/g of total extracted protein) in four genotypes of mature amaranth seeds, showing a match of over 60% with the lunasin peptide sequence found in soybeans known to have anticancer properties.

To confirm these benefits and better understand the mechanisms of action, further research, particularly focused on bioavailability and clinical studies, is necessary. The integration of amaranth into the diet may represent a useful contribution to the preservation and enhancement of health, but for a complete confirmation of its benefits, more scientific data is needed. Amaranth has been suggested as a dietary supplement that can promote bone health due to its high calcium content, can assist blood sugar regulation due to its high manganese levels, and can help cure folic acid shortage in pregnant women to prevent spina bifida and heart problems in newborns (Soriano-García *et al.*, 2018; 2019). In India, traditional healers employed an extract of *A. spinosus* L. whole plant to treat jaundice and liver enlargement (Sundaram and Suresh, 2019). In Africa, leaves of amaranth are used as a nutraceutical or functional food to treat tooth emergence in infants. It is used as a diuretic to treat worms and to treat stomachaches and constipation (Gandhi *et al.*, 2020).

Oil from seeds of *A. cruentus* it can be used in cosmetic formulations of anti-aging creams and as a natural sun protection factor (SPF) component (Wolosik *et al.*, 2017). It has been found that duodenal peptic ulcer and chronic gastritis caused by *Helicobacter pylori* can be treated with amaranth oil (Cherkas *et al.*, 2018).

Conclusions

Amaranth is a pseudo-cereal crop for food and health-promoting product. Amaranth has an area of increasing scientific interest due to its valuable biological properties, rich phytochemical composition, and wide pharmacological activity. Amaranth is an important traditional plant that has been used in folk medicine for centuries. According to research findings, amaranth has the ability to enhance the functionality of the immune system, facilitated by its outstanding balance of amino acid composition, as well as the ratio of lysine to arginine. The high antioxidant capacity of *Amaranthus* spp. is attributed to high levels of polyphenolic compounds, especially flavonoids, amaranthine, and ascorbic acid. The results obtained in this study indicate that the variability in protein content, amino acids, and total phenolic compounds is largely influenced by genetic factors. The results show significant values of total proteins and essential amino acids for the examined genotypes. In amaranth leaves, the lysine content ranged from 3.9 g/100 g to 7.0 g/100 g depending on the genotype, while the lysine content ranged from 4.2 g/100 g to 6.7 g/100 g in amaranth flowers. The results of the studies presented in this review provide a detailed analysis of the health effects of extracts from different biological parts, referring to the main bioactive components of *Amaranthus* spp. However, the bioavailability

and underlying mechanism of action of ingredients from this source have not been investigated and require focused clinical research in the future.

Authors' Contributions

Conceptualization, A.S., V.P., J.B., V.P.; methodology, A.F., V.P. and A.S.; software, V.P.; validation, A.F.; formal analysis, T.M., A.S., V.P.; investigation, V.P.; resources, V.P., A.St.; data curation, V.P.; writing-original draft preparation, A.S., J.B., V.P.; writing-review and editing V.P., A.F., T.M., V.P.; visualization, A.S., V.P., V.P., A.St.; supervision, M.B., A.S., J.B., V.P.; project administration, V.P.; funding acquisition, A.S., J.B. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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