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Comparative characteristics of the amino acid composition in amaranth accessions from the VIR Collection

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Abstract: The development of products that fully meet the criteria for a healthy diet is one of the main trends in nutrition quality improvement worldwide. Amaranth, a leader in protein quality, has significant potential. A comparative study of the protein complex in leaf biomass has been conducted for the first time for *Amaranthus* spp. grown for various uses. The aim of the study was to analyze the characteristics of the amino acid composition and identify the relationships among its components in the amaranth leaf biomass. For this purpose, gas–liquid chromatography coupled with mass spectrometry was employed. Based on the data of 42 amaranth accessions, the most constant biochemical indicators were identified. Amino acid composition in amaranth accessions, represented by 18 amino acids, had the closest relationship with the content of ascorbic acid and dry matter. The absence of a significant association of lysine and proline with other amino acids was revealed. The amino acid profile had a strong positive relationship with most components, but it was not balanced in composition. Weedy amaranth species are of interest for practical utilization due to their high content of phenolic compounds and lysine. Grain amaranth species were better balanced in amino acids and generally showed the highest protein levels. These are recommended as a source of highly balanced amino acid composition.

Key words: *Amaranthus* L., biochemical characteristics, amino acid profile, factor analysis, correlation, lysine

1. Introduction

Solutions to the task of food quality improvement may be found through the development of products enriched with crude plant components, especially those with a high-quality protein composition. Amaranth is numbered among the crops that yield such ingredients (Sanz-Penella et al., 2012; Derkanosova et al., 2015; Gins et al., 2017a). Amaranth (*Amaranthus* L.) is a cultivated plant with great potential in growth rate, productivity, and high content of complete protein in its grain and leaf biomass (Kononkovet al., 1998). Its high nutritional value is based on the content of basic trace elements, such as β-carotene, iron, calcium, vitamin C, folic acid, etc. (Aletoret al., 2002; Priya et al., 2007; Gins et al., 2017b). It deserves to be considered an important vegetable, grain ('pseudocereal'), forage, melliferous, and medicinal crop. Amaranth contains red-violet betacyanin pigments, so it may be used as a natural food dye. Figure 1 shows the universal nature of amaranth utilization.

It is known that the main quality indicator of protein is its amino acid composition, specifically the content of essential acids. Amaranth is a record breaker in the content of complete protein: it is not without reason that this crop is called 'a protein repository', and its leaf biomass rivals seafood in calories. Its value is based on an optimal ratio of amino acids and on a considerable amount of sulfur-containing amino acids and lysine. A complete set of essential amino acids in amaranth leaves, which determines their high nutritional and pharmacological value, is the basis for producing protein food additives from leaf biomass (Gins et al., 2019). Of late, the ever-growing attention of the world community has been drawn to the use of amaranth as a source of amino acids for the pharmaceutical industry (Montoya-Rodrıguez et al., 2015).

The need to study the amino acid composition in amaranth, as a chain link in the human nutritional profile and in view of the crop's pharmacological value, grows with every year. This crop is distinguished for its rich genetic diversity, phenotypic plasticity, high adaptability to unfavorable growing conditions, and tolerance to high temperatures and droughts. Amaranth does not

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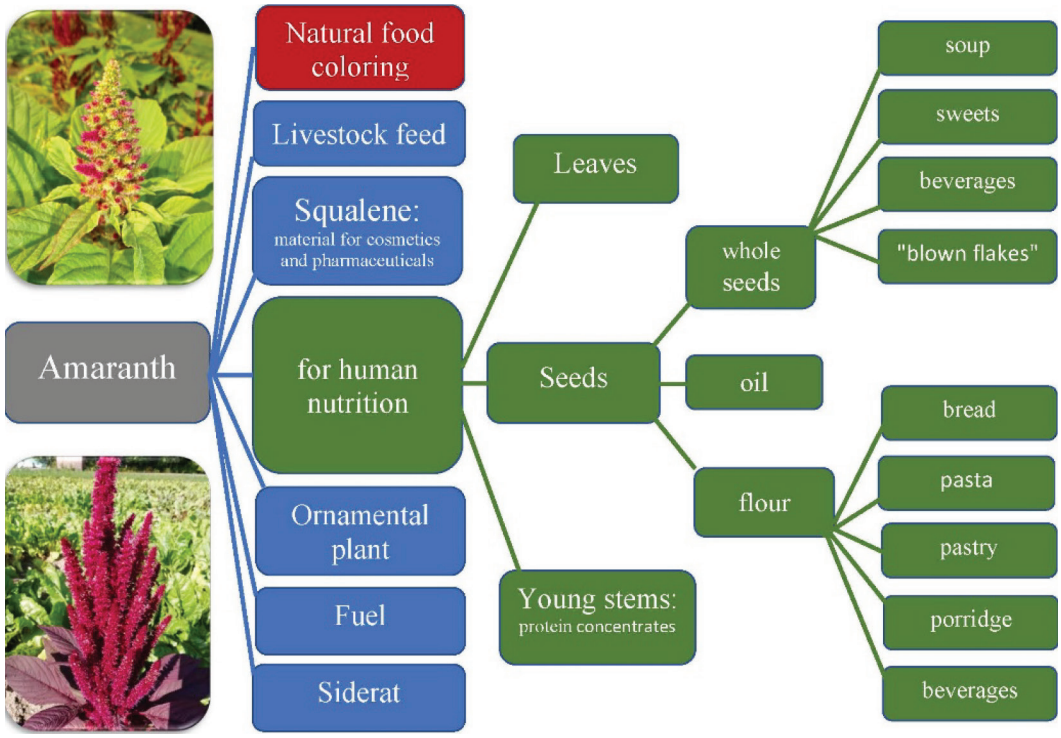

Figure 1. A generalized flowchart showing the uses of amaranth.

face serious problems with diseases or pests and is one of the most undemanding crops in terms of applicable agricultural practices (Barrio and Anon, 2010; Rastogi and Shukla, 2013). The rich amino acid composition of amaranth is a feasible tool to solve the problems of famine and undernourishment in developing countries, as it may enrich the habitual foods (Muhali et al., 2018). Folk medicine in the countries of Latin America, India, and Africa, with their inherent systems of traditional healthcare approaches, has been using various parts of amaranth plants for ages against lung, kidney, gastrointestinal, and skin diseases (Caselato-Sousa and Amaya-Farfan, 2012). Profound research is required to disclose the potential of amaranth for pharmacology.

Broad genetic diversity of amaranth maintained in the VIR collection is of interest as material for research. The aim of this study was to explore the specific features of the leaf biomass composition in amaranth accessions grown for various purposes and assess the relationships between biochemical parameters and protein content in them.

2. Materials and methods

Forty-two amaranth accessions (12 spp.) from the VIR collection served as the material for this research. The accessions were grown as part of the vegetable rotation in the fields of Pushkin and Pavlovsk Laboratories of VIR (Town of Pushkin, St. Petersburg, Russia) from 2015 through to 2018. Biomass was collected for analysis in the last third of August. The biochemical analysis was implemented at the Biochemistry and Molecular Biology Laboratory of VIR. The plant material was analyzed and treated according to VIR's guidelines (Ermakov et al., 1987; Solovyeva et al., 2019). Dry matter content was measured by weighing the average sample before and after drying in a drying cabinet at 105 °C; ascorbic acid content by titration with Tillman's reagent; protein content by the Kjeldahl method on a Kjeltec Auto 1030 Analyzer, Sweden; saccharide, free amino acid, organic acid, and phenolcarboxylic acid compositions by gas–liquid chromatography with mass spectrometry. For metabolomic profiling, 10 g of an accession was weighed and homogenized with an adequate amount of ethanol; then, the sample was infused for 30 days at 5–6 °C. The extract (200 µL) was vaporized to dryness on a CentriVap Concentrator (Labconco, USA). The dry precipitate was silylated with bis(trimethylsilyl) trifluoroacetamide. Silylated compounds were separated on an HP-5MS capillary column (5% phenyl 95% methylpolysiloxane, 30.0 µm, 250.00 µm, 0.25 µm) using an Agilent 6850 chromatograph with a quadrupole mass selective detector (Agilent 5975B VL MSD, Agilent Technologies, USA). Conditions of the chromatographic analysis were as follows: Helium flow in the column was 1.5 mL / min. Heating program for the column was from +70 °C up to +320 °C, at a heating rate of 4 °C / min.

Mass selective detector temperature was +230 °C; sample injector temperature +300 °C; sample size 1 μL. Tricosane solution in pyridine (1 μg / μL) served as the internal standard (Jonsson et al., 2004; Smolikova et al., 2015). Libraries used in the process of analysis were NIST2010 (National Institute of Standards and Technology, USA), and the collections of standard compound mass spectra maintained by St. Petersburg State University and the Komarov Botanical Institute, with an affinity index no less than 80 (Shtark et al., 2019). Software used: UniChrom; AMDIS (Automated Mass Spectral Deconvolution and Identification System). The resulting experimental data were processed by the methods of statistical analysis using Excel and Statistica 7.0 software. Variability in the structure of relationships among characters was assessed by means of factor analysis. Factor loadings were calculated using the method of principal components. Correlation coefficients $r < 0.5$ were regarded as low, $0.7 > r \geq 0.5$ as medium, $0.9 > r \geq 0.7$ as high, and $r \geq 0.9$ as very high.

3. Results and discussion

The genus *Amaranthus* L. includes, according to different data sources, from 60 to 100 species. Representing a small group of so-called 'pseudocereals', it is the most widespread and very complicated as far as its taxonomy is concerned (Saunders and Becker, 1984; Teutonico and Knorr, 1985). The majority of its species originated in the North and South Americas (Costea et al., 2001). *Amaranthus* L. has been the target of numerous research studies, but nevertheless, the scope of many species and boundaries between them have not yet been outlined clearly enough (Iamonico and Mokni, 2018). Taxonomic characteristics of many amaranths are very much alike. Their most important diagnostic characters are morphological features of the inflorescence, flower, fruit, and, for some of the species, the shape of the leaf blade. The phenotype of an individual species is greatly influenced by environmental factors, such as access to nutrients and moisture, light conditions, daylight duration, etc., which results in considerable intraspecific phenotypic variability. Amaranth species are extremely diverse morphologically, but still their genomes are quite similar. Many species are freely intercrossable and produce intermediate forms. The ever-going interspecies hybridization contributes to the smearing of boundaries between species. All these peculiarities of the crop have led to erroneous duplicate naming of its species, taxonomic confusion, and the existence of a vast number of nomenclatural synonyms (Mosyakin and Robertson, 1996; Trucco et al., 2005). Considering the abovementioned facts, we have chosen the approach to amaranth evaluation based on the purposes for which its species are used. According to their economic value, amaranths are conventionally classified into several groups: food (grain and leaf), feed, industrial, and weedy. Many of them demonstrate distinctly expressed ornamental properties (Sauer,1967). The content of secondary metabolites underpins the medicinal value of many *Amaranthus* spp. (Kim and Lee, 1988).

The subdivision of amaranths according to their fitness for food purposes is conditional enough (Table 1). Despite the fact that young plants of practically all cultivated species are edible as greens, a number of species can be singled out as predominantly vegetable ones. Initially, the cultivation of this crop followed two basic trends: for

Table 1. *Amaranthus* spp. selected for the experiment and their possible uses.

Species included in the experiment	Number of accessions	Possible uses		
		Grain	Vegetable	Weedy
Amaranthus lividus L.	3	–	+	+
Amaranthus caudatus L.	4	+	+	–
Amaranthus cruentus L.	8	+	+	–
*Amaranthusdubius*Mart. ex Thell.	3	–	+	–
Amaranthus hypochondriacus L.	5	+	–	–
Amaranthus tricolor L.	3	–	+	–
Amaranthus retroflexus L.	1	–	–	+
Amaranthus graecizans L.	3	–	+	+
Amaranthus albus L.	1	–	–	+
Amaranthus gangeticus L.	6	–	+	–
Amaranthus hybridus L.	4	+	–	–
Amaranthus powellii S. Watson	1	–	–	+

edible seeds (Central and South Americas, mountainous areas in Asia) and for greens (Africa, South and Southeast Asia). Dr. Girenko (1995) identified in the VIR collection accessions of the following *Amaranthus* spp. as source materials for breeding vegetable amaranth cultivars: *A. caudatus* L., *A. dubius* Mart. ex Thell, and *A. tricolor* L., with three varieties, recognized by some taxonomists as independent species: var. *tricolor*, var. *gangeticus* Fiori et Paol., and var. *mangostanus* Thell. Besides, VIR holds in its collection ancient cultivated amaranth species, still grown as leafy vegetable crops, such as *A. blitum* L., *A. spinosus*, *A. viridis* L. and *A. graecizans* L. (subsp. *silvestris* (Vill.)). The cultivation of grain amaranth forms of American origin as vegetables is typical for African countries.

Stability of the biochemical indicator in question depends on the scope of its variation. Biochemical analysis of leaf biomass disclosed a wide range of variation for some indicators and identified more stable ones. The most constant indicators were the contents of dry matter and protein (Figure 2). Regardless of the purpose for which an accession is supposed to be used, the coefficients of variation (Cv %) for dry matter and protein did not exceed 33%, varying within the range of 8.64 to 21.32% for dry matter, and 8.76 to 28.19% for protein. Protein content in all amaranth accessions in the experiment showed insignificant variation (Cv 18.5%–24.8%). The species used as vegetables were not stable in most of the indicators: organic acids, phenolic components, pigment composition, fatty acids, ascorbic acid, and in particular the content of free amino acids.

On the whole, the species grown for grain showed more stable component composition of leaf biomass in all indicators (Table 2). It is in line with the molecular biology data concerning proximity of their origin. Amaranths used as vegetables demonstrated a wide range of variability in the content of saccharides, phenolic compounds, and fatty and organic acids. The amino acid content also fluctuated significantly within all studied groups. The highest level was recorded for an accession of *Amaranthus lividus* L. grown for vegetable use (pk-223, Bangladesh): 477.25 mg/100 g.

One of the top-priority functions of phenolic compounds is effective protection of plants against stressors. Larger amounts of volatile phenolics were identified in weedy species, thus confirming their higher adaptability to negative environmental effects. The highest phenolic content, however, was observed in an accession of *Amaranthus dubius* from Venezuela: 322.65 mg/100 g. It should be noted that caffeic acid and its synthetic derivative, ferulic acid, was predominant among all phenolics in the tested amaranth accessions. These secondary metabolites possess well-expressed antioxidant properties and are able to produce a wide spectrum of pharmacological effects on a human organism. Weedy amaranth species are of special interest as sources of such medicinal effect.

Analyzing the structure of interrelations among biochemical indicators (principal component analysis, PCA) resulted in identification of three approximately equivalent factors (Table 3). Factor 1, with its strong interrelations, united the indicators associated with the taste of amaranth accessions. Factor 3 manifested close positive correlations between the indicators of 'productivity': dry matter, amino acids content, and ascorbic acid. The 'pigment' indicators in factor 3 had the

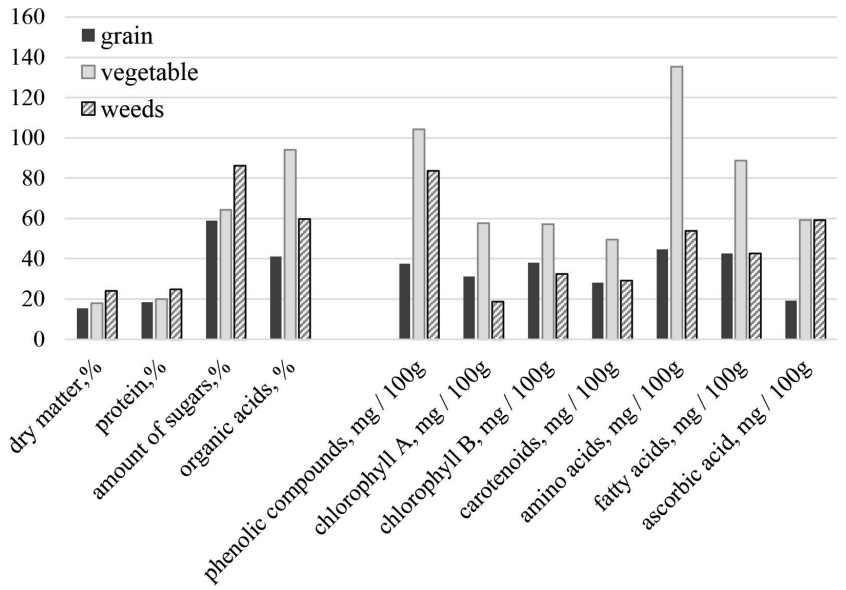

Figure 2. Variability ranges of biochemical parameters in amaranth leaf biomass (Cv).

closest relationships, i.e., accounted for a major part of dispersion. At the same time, dispersion of other variables was also high, thus confirming a significant contribution of each of them.

The 3D graph showing principal components of the factor analysis makes it clear that the amino acid composition of amaranth leaf biomass has the closest relationship with the contents of ascorbic acid and dry matter (Figure 3). The pigment indicators of the above ground plant parts (Factor 2) did not have a significant effect on the protein content. The fatty acid composition showed a strong positive correlation with that of amino acids (r = 0.71). In the group of vegetable amaranths this correlation was 0.9%, in the weedy group 0.79%, and in the grain group 0.57 .

A specific feature of amaranth is a considerable amount of highly-digestible gluten-free protein in seeds: it is higher than the same indicator in traditional cereals, such as rye, maize, or rice (Grobelnik-Mlakar et al., 2009). Amaranth also exceeds these crops in the content of essential amino acids: lysine, methionine, isoleucine, valine. and tryptophan. Lysine is a vitally important amino acid, and

Table 2. Comparative data of biochemical indicators in amaranth leaf biomass used for various purposes.

Indicators	M±Sx, (Cv, %), Median (min÷max)*		
	Grain forms	Vegetable forms	Weedy forms
Dry matter, %	**16.98**±0.77 (15.5)	12.1±0.53 (17.9)	15.54±1.25 (24.05)
Ascorbic acid, mg/100g	**73.5**±3.9 (19.3)	24.12±3.47 (59.3)	46.13±9.1 (59.1)
Amount of sugars, %	0.66±0.11 (59.0)	0.45 (0.01÷1.19) *	0.55 (0.31÷2.73) *
Organic acids, %	0.94±0.11 (41.1)	0.52 (0.27÷3.67) *	0.76±0.15 (59.6)
Phenolic compounds, mg/100g	85.2±8.9 (37.5)	42.43 (14.04÷307.2) *	100.3 (15.7÷**322.6**) *
Chlorophyll A, mg/100 g	103.9±9.0 (31.1)	103.75±14.5 (57.7)	110.14±6.9 (18.8)
Chlorophyll B, mg/100 g	33.29±3.51 (38.0)	36.29±5.02 (57.0)	41.0±4.42 (32.35)
Carotenoids, mg/100 g	34.0±2.64 (28.0)	32.2±3.86 (49.5)	36.75±3.58 (29.3)
Protein, %	**20.4**±1.05 (18.5)	14.1±0.68 (19.9)	16.7±1.38 (24.8)
Amino acids, mg/100 g	**218.45**±27.0 (44.6)	44.27 (4.54÷**477.2**) *	103.71±18.6 (53.9)
Fatty acids, mg/100 g	73.8±8.71 (42.5)	26.64 (2.0÷**150.9**) *	48.11±6.86 (42.8)

*The data have abnormal distribution.

Table 3. The factor analysis results for biochemical indicators in raw biomass of amaranth.

Variable	Factor* (Varimax raw)			Communality
	1	2	3	
Dry matter	0.11	–0.08	**0.84**	0.57
Ascorbic acid	0.12	–0.05	**0.86**	0.72
Sugars	**0.82**	0.01	0.19	0.74
Organic acids	**0.64**	–0.24	0.22	0.69
Phenolic compounds	**0.93**	–0.02	0.04	0.83
Chlorophyll	0.02	**0.97**	–0.06	**0.90**
Carotenoids	–0.01	**0.98**	0.04	**0.91**
Amino acids	0.32	0.09	**0.79**	0.86
Fatty acids	**0.76**	0.16	0.49	0.86

*Interpretation of factors: 1 – taste indicators, 2 – pigments, 3 – productivity.

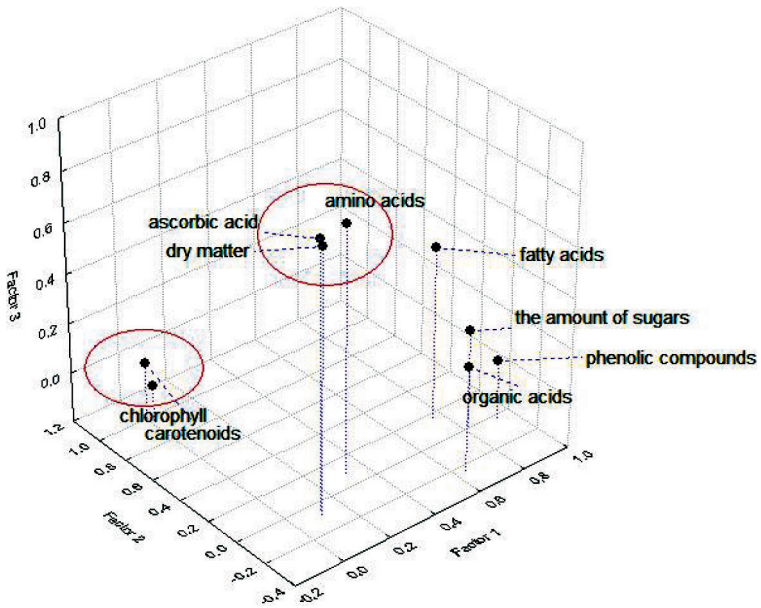

Figure 3. A 3D graph showing contributions of principal components to the total dispersion.

amaranth seeds contain 2.5× more lysine than wheat, and 3× more than maize (Zheleznov, 2005). Considering the high potential of amaranth as a green vegetable, it was interesting to study the characteristics of amino acid composition in its leaf biomass.

Eighteen free amino acids were identified in the leaf biomass of the tested amaranth accessions, including 8 essential (valine, isoleucine, leucine, methionine, lysine, tryptophan, threonine, and phenylalanine), 3 partially nonessential (arginine, histidine, and tyrosine), and 7 nonessential (alanine, glycine, serine, proline, cystine, aspartic, and glutamic acids) amino acids (Table 4). The issue concerning proper grouping of amino acids has been actively investigated by the scientific community: some of these acids are recognized as conditionally dispensable. Partially essential amino acids can be synthesized in the human organism, although in insufficient amounts. Such amino acids are arginine, histidine, and tyrosine. In this study, the amaranth species cultivated for grain were the leaders in the content of total amino acids. With this, the range of variation in values for this group of species was the narrowest, which proves the homogeneity of the breeding material, as a result of the efforts taken by breeders to obtain genetically uniform cultivars, and the proximity of the species' origin. Grain amaranths originated from the New World: *Amaranthus caudatus* L. from the Andean Cordillera, namely Ecuador and Peru; *Amaranthus cruentus* L. and *Amaranthus hypochondriacus* L. from Mexico and Central America (Covas, 1994). At present, amaranth is cultivated as a cereal crop in Europe and both Americas, and as a vegetable in Africa and Southeast Asia.

Alanine, glutamic, and aspartic acids are the first in the descending order of amino acids among all tested accessions. Alanine is a building component for some proteins and vitamins; it raises the level of energy metabolism, stimulates immunity, and regulates the level of sugar in human blood. The highest content of alanine was identified in an accession of *A. hypochondriacus* (pk-287, Mexico): 143.6 mg/100 g. The same accession was also notable for high contents of glutamic and aspartic acids in its leaves. Glutamic acid is one of the most important amino acids in plant and animal proteins. Its highest content was observed in the vegetable amaranth cultivar 'White stem' (pk-223, Bangladesh): 83.9 mg/100 g.

The descending hierarchy in the essential amino acid content of amaranth accessions was as follows: Lys > Val > Leu > Met > Ile > Phe > Trp > Thr. Lysine is an amino acid indispensable for the normal functioning of a human organism. It is present in practically all of the organism's proteins, being the first of the limiting amino acids required for normal assimilation of food proteins. This amino acid is restored, in the first place, through consuming products of animal origin, and also those produced from leguminous plants: soybean, common beans, and peas. In this study, the content of lysine in amaranth biomass exceeded the levels observed in legumes, reaching on average 6.8 mg/100 g, which complied with the data of other researchers (Aletor, 2005). The species grown for grain demonstrated high lysine content (6.47 mg / 100 g) and an insignificant range of its variation. The group of weedy accessions, on the contrary, was extremely variable in the lysine content: from 1.0 up

Table 4. Amino acid profiles in the leaf biomass of amaranth accessions depending on the purpose of their use (mg/100 g).

Amino acid		Mean, mg/100g			Median (min÷max)
		Pseudocereal	Vegetable	Weedy	
Asp	Aspartic acid	26.27	9.77	10.96	8.0 (0.3÷73.5)
Asn	Asparagine	1.71	0.17	0.65	0.5 (0÷2.8)
Ile	Isoleucine *	5.25	1.74	2.25	2.0 (0÷10.9)
Thr	Threonine *	3.65	0.91	2.55	1.8 (0.1÷21.0)
Met	Methionine *	6.37	4.03	4.09	3.9 (0.6÷19.5)
Lys	Lysine *	6.47	2.71	**14.25**	2.9 (0.1÷91.5)
Glu	Glutamic acid	27.84	18.21	19.23	17.7(0.3÷83.9) **
Gln	Glutamine	9.98	0.94	4.04	2.5 (0÷24.5)
Pro	Proline	3.19	0.87	1.48	1.2 (0÷20.7)
Ala	Alanine	46.14	15.33	16.11	12.7 (0.7÷143.6)
Val	Valine *	13.74	3.42	6.06	6.2 (0.3÷24.2)
Leu	Leucine *	12.96	2.75	4.55	3.9 (0÷22.4)
Ser	Serine	12.67	4.37	6.07	5.3 (0.6÷21.8)
Gly	Glycine	1.47	0.51	0.90	0.7 (0÷3.8)
Cys	Cystine	0.30	0.10	0.22	0.2 (0.01÷0.7) **
Trp	Tryptophan*	3.65	0.91	2.70	1.8 (0÷8.7)
Phe	Phenylalanine*	4.21	1.76	2.14	1.9 (0÷13.5)
Tyr	Tyrosine	3.27	0.36	2.90	1.5 (0÷15.2)

*Essential amino acids.
**The data with normal distribution.

to 91.5 mg/100 g. Biosynthesis of this amino acid in the single species *Amaranthus lividus* L., represented in the study by three accessions, went on at different rates. In one case (vk-129, Bangladesh), the plants accumulated 1.8 mg/100 g of lysine up to the time when the plant material was collected for analysis; in the second case (vk-107, Portugal), 16.7 mg/100 g, and in the third (pk-31, India), 91.5 mg/100 g. The latter amaranth accession from India (pk-31) is of special interest: its lysine parameters more than 10× exceeded the mean value (Figure 4).

Correlation analysis of the crop's amino acid profile showed the absence of statistically significant relationships between lysine and other amino acids (Table 5). An exception was observed in the group of weedy species, where lysine demonstrated a strong positive correlation with tyrosine, tryptophan, and cystine. This exception is explained by the maximum values of these indicators observed in the abovementioned accession (pk-31).

Comparison of the interplay across the three groups of accessions showed significant differences. For example, aspartic acid (*Asp*) in the grain and weedy groups did not show statistically significant correlations with other amino acids, while in the vegetable species this acid had a strong positive correlation with valine, alanine, glycine, serine, leucine, and threonine (r = 0.71–0.94).

As an element of the plant defense system, proline possesses osmoregulation and antioxidant properties as well as the ability to prevent enzyme inactivation and cell membrane and organelle damage (Kuznetsov and Shevyakova, 1999; Atkin and Macherel, 2009). Accumulation of a considerably higher content of proline in the group of grain amaranth species proves their better adaptability to abiotic stressors, such as moisture deficit or soil salinization, which may be explained by their origin. It is worth mentioning that proline is the only amino acid that has no direct correlations with other amino acids.

On the whole, the amino acid profile in vegetable amaranths was closely correlated. Such amino acids as phenylalanine, tryptophan, and aspartic acid had a strong positive correlation with the total set of amino acids. At the same time, their composition is not balanced and differs considerably depending on an individual accession.

Figure 4. The accession of *Amaranthus lividus* L. (pk-31, India).

4. Conclusion

The research ascertained that the most constant biochemical indicators in amaranth leaf biomass were the contents of dry matter (Cv 8.64%–21.32%) and protein (Cv 18.5%–24.8%). Principal component analysis showed that the amino acid content in amaranth leaf biomass has the closest interrelationship with the contents of ascorbic acid and dry matter. Also observed was a strong correlation between the said indicator and the fatty acid composition. No correlations were recorded between the pigment composition responsible for the color of above ground plant organs and the protein content. Leaf biomass of the tested plants was found to contain 18 free amino acids, including 8 essential ones. Amaranth accessions of the grain group were better balanced in their amino acid composition, and in total demonstrated the highest values. On the whole, amaranth species grown as leafy vegetables had lower values of most indicators, such as organic acids, phenolic compounds, pigment composition, fatty acids, ascorbic acid, and, in particular, the content of free amino acids. The accession from Bangladesh (pk-223) was an exception: it had the highest amino acid content among all tested accessions (477.25 mg/100 g).

Correlation analysis of the crop's amino acid profile revealed the absence of any significant correlation of lysine and proline with other amino acids. In the group of vegetable amaranths, the amino acid profile had a strong positive interplay among most of the components, but was not balanced in its composition.

From the viewpoint of the medicinal effect on the human organism due to a high content of phenolics and lysine, the weedy amaranth species demonstrated considerable potential. Of special interest for further research is the accession of *Amaranthus lividus* L. from

Table 5. The correlation matrix of the amino acid profile in amaranth leaf biomass.
Grain forms

	Ala	Gly	Ser	Leu	Pro	Thr	Asp	Glu	Asn	Gln	Tyr	Trp	Cys	Lys	Ile	Met	Phe
Val	0.72	0.76	0.68	0.85	0.43	**0.95**	0.52	0.86	0.69	0.48	0.87	0.49	0.36	–0.39	0.88	0.31	0.65
Ala		**0.90***	0.38	0.83	0.64	0.81	–0.04	0.65	0.39	0.09	0.58	0.36	0.04	–0.22	0.62	–0.14	0.05
Gly			0.52	0.75	0.43	0.81	0.06	0.73	0.50	0.27	0.58	0.40	0.17	–0.23	0.59	–0.03	0.27
Ser				0.67	–0.25	0.69	0.56	0.75	0.43	0.64	0.49	0.66	0.37	–0.18	0.54	0.53	0.66
Leu					0.40	0.86	0.31	0.80	0.57	0.50	0.73	0.58	0.39	–0.37	0.68	0.24	0.29
Pro						0.45	–0.19	0.13	0.25	–0.26	0.47	–0.02	–0.17	–0.25	0.53	–0.23	–0.12
Thr							0.39	**0.90**	0.54	0.35	0.81	0.53	0.14	–0.32	0.86	0.23	0.51
Asp								0.48	0.53	0.53	0.55	0.24	0.42	–0.24	0.60	0.31	0.78
Glu									0.53	0.45	0.76	0.45	0.33	–0.31	0.71	0.22	0.54
Asn										0.73	0.70	0.28	0.58	–0.29	0.63	0.36	0.50
Gln											0.44	0.58	0.70	–0.13	0.27	0.73	0.45
Tyr												0.39	0.37	–0.20	0.82	0.20	0.63
Trp													0.31	0.26	0.34	0.63	0.28
Cys														–0.14	0.18	0.41	0.32
Lys															–0.36	0.01	–0.21
Ile																0.20	0.62
Met																	0.38

Vegetable forms

	Ala	Gly	Ser	Leu	Pro	Thr	Asp	Glu	Asn	Gln	Tyr	Trp	Cys	Lys	Ile	Met	Phe
Val	0.89	0.57	**0.99**	**0.95**	0.39	**0.90**	**0.94**	0.85	0.49	0.53	0.47	0.72	0.23	0.68	**0.91**	0.84	0.88
Ala		0.69	0.89	**0.91**	0.67	0.67	**0.98**	0.68	0.80	0.82	0.77	0.89	–0.02	0.65	0.88	0.54	0.81
Gly				0.59	0.62	0.31	0.71	0.33	0.68	0.75	0.70	0.65	0.01	0.53	0.58	0.34	0.49
Ser				0.95	0.41	**0.90**	**0.94**	0.84	0.50	0.55	0.48	0.76	0.23	0.65	**0.92**	0.82	0.88
Leu					0.38	0.85	**0.94**	0.78	0.55	0.60	0.61	0.81	0.12	0.56	**0.99**	0.68	0.81
Pro						0.07	0.61	0.14	0.84	0.85	0.71	0.71	0.07	0.57	0.35	0.08	0.35
Thr							0.76	**0.90**	0.16	0.19	0.12	0.50	0.31	0.37	0.83	0.85	0.80
Asp								0.73	0.73	0.77	0.69	0.86	0.06	0.68	**0.92**	0.64	0.83
Glu									0.17	0.18	0.13	0.44	0.35	0.33	0.75	0.84	**0.95**
Asn										**0.97**	0.89	0.81	–0.29	0.55	0.54	0.06	0.38
Gln											**0.94**	0.86	–0.22	0.61	0.59	0.09	0.41
Tyr												0.84	–0.26	0.54	0.62	0.01	0.36
Trp													0.01	0.51	0.81	0.30	0.60
Cys														0.10	0.09	0.46	0.28
Lys															0.53	0.57	0.50
Ile																0.63	0.78
Met																	0.79

Table 5. (Continued).

Weedy forms

	Ala	Gly	Ser	Leu	Pro	Thr	Asp	Glu	Asn	Gln	Tyr	Trp	Cys	Lys	Ile	Met	Phe
Val	0.66	0.63	0.69	**0.94**	0.04	0.88	0.62	0.54	0.85	0.81	0.30	0.64	0.18	0.11	**0.92**	0.22	0.29
Ala		0.81	0.80	0.80	0.19	0.58	0.20	0.61	0.38	0.31	–0.13	0.03	–0.26	–0.32	0.58	–0.10	0.00
Gly			0.84	0.72	–0.18	0.67	0.18	0.42	0.35	0.21	0.22	0.21	0.07	0.04	0.53	0.24	0.32
Ser				0.75	–0.12	0.65	0.40	0.58	0.55	0.51	0.13	0.30	0.23	–0.05	0.73	0.18	0.08
Leu					–0.06	0.81	0.43	0.45	0.72	0.64	0.15	0.45	–0.01	–0.06	0.87	0.06	0.15
Pro						0.11	0.02	0.63	0.00	0.15	–0.06	0.04	–0.28	–0.05	–0.13	0.02	0.14
Thr							0.48	0.63	0.66	0.69	0.64	0.81	0.36	0.47	0.74	0.61	0.60
Asp								0.46	0.73	0.86	0.08	0.40	0.48	0.00	0.78	0.15	–0.02
Glu									0.38	0.57	0.21	0.39	0.20	0.10	0.48	0.34	0.35
Asn										**0.91**	0.14	0.55	0.15	–0.02	0.85	0.06	0.00
Gln											0.24	0.65	0.38	0.11	0.87	0.22	0.08
Tyr												0.87	0.67	**0.97**	0.15	**0.96**	0.85
Trp													0.64	0.79	0.53	0.79	0.69
Cys														0.70	0.32	0.74	0.48
Lys															–0.02	**0.95**	0.83
Ile																0.11	0.04
Met																	0.83

*Highlighted in bold are correlation coefficients 0.9–1.0 (strong degree)

India (pk-31), the leader in the content of ascorbic acid (90.2 mg/100 g), sugars, organic acids, phenolic compounds, and fatty acids, with a capability to accumulate up to 90.53 mg/100 g of lysine as well as sizable amounts of tyrosine, tryptophan, and cystine. The research results make it possible to recommend, as sources of highly balanced amino acid composition in leaf biomass, the following amaranth species grown for grain: *Amaranthus caudatus* L., *Amaranthus cruentus* L., and *Amaranthus hypochondriacus* L.

Conflict of interest

The authors declare that they have no conflict of interest.

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