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REVIEW

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An update on the nutritional profiles of quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* spp.), and chia (*Salvia hispanica* L.), three key species with the potential to contribute to food security worldwide

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Abstract

One of the major challenges facing the world nowadays is to ensure enough access to healthy food for a growing population. Under this food scenario, it should be noted that increasing food production is as important as improving its nutritional quality. Thus, different agronomy research and innovation programs have pursued food security through the increase in the quantity and nutritional quality of plant-based foods. One key aspect in this respect is to increase agrobiodiversity by expanding the cultivation of underutilized highly nutritious crops such as chia, quinoa, or amaranth. The outstanding nutritional value of these crops resides in the compositional characteristics of their seeds, which include the presence of significant levels (and a good balance) of proteins, essential amino acids, lipids, and other components such as phenols, minerals, fiber, or vitamins, all contributing to support nutritious diets that also has health benefits such as the prevention of cardiovascular diseases. All of them, chia, amaranth, and quinoa, are considered emerging crops outside their center of origin (which is mainly located in South America), and their cultivation has been expanded worldwide in the last decade. This review mainly highlights recent knowledge about the nutritional characteristics of these three Latin American crops, with the aim of providing an updated information regarding the compositional profiles of their seeds.

KEYWORDS
Amaranthus, Chia, nutritional properties, Quinoa, seeds

INTRODUCTION

According to the Food and Agriculture Organization of the United Nations (FAO), the world is in a precarious position in regard to feeding our future world population. More than 50,000 edible plant species exist in the world, but only a few hundred contribute significantly to food supplies. Only 15 crop plants provide 90% of the world's food energy intake, with three (rice, maize, and wheat) making up two-thirds of this (Figure 1). These three are the staples of over 4000 million people. However, millions of people around the world suffer from a lack of a balanced nutritious diet, which will likely rise as the global population expands to an estimated 10 billion by 2050.[1–3]

Meanwhile, climate change is unleashing weather conditions, pests, and diseases that our current crops struggle to cope with. This

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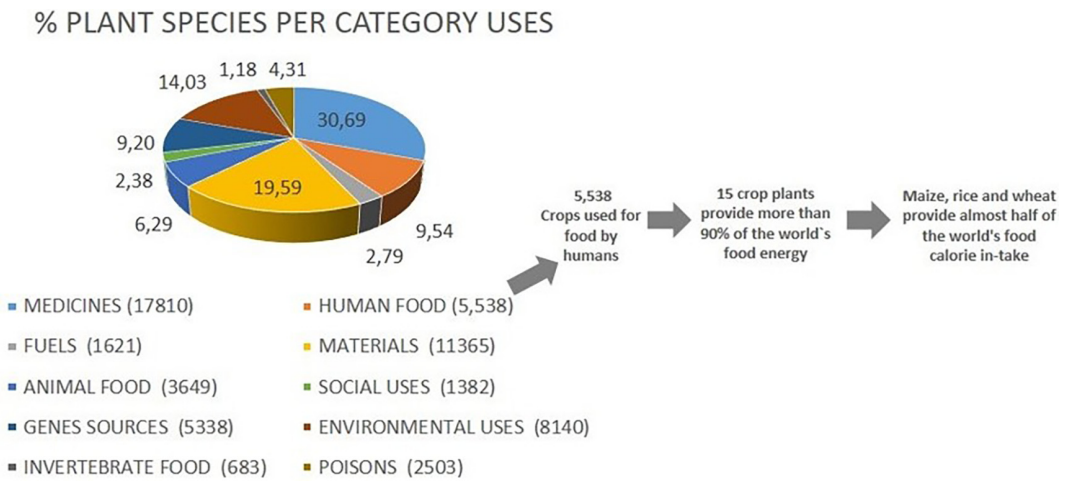

FIGURE 1 Catalogue of useful plant species classified by their uses. As indicated in the figure, among the 5538 plant species used for food, 15 plant species are providing 90% of the food energy.[1–3]

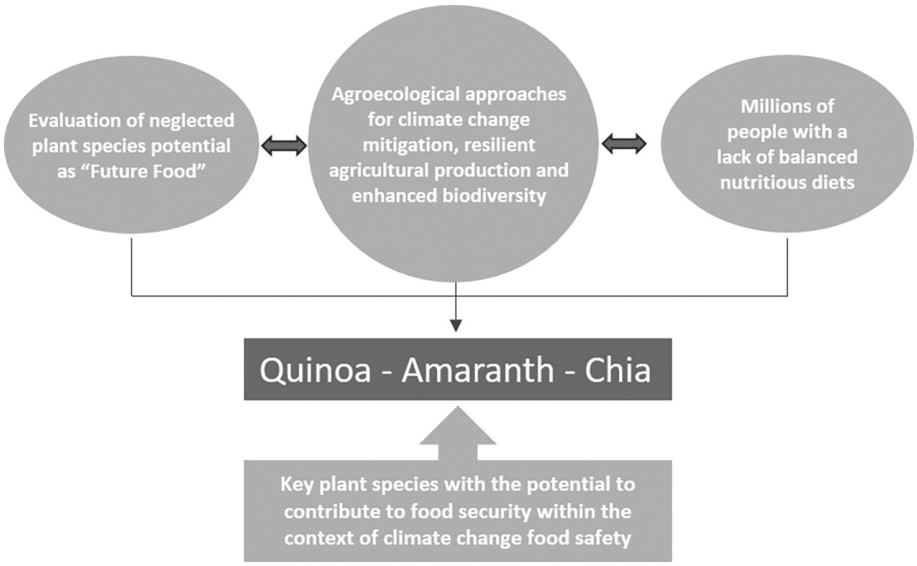

FIGURE 2 Scheme of potential applications and contributions of the neglected and underutilized species quinoa, amaranth, and chia.

is a consequence, at least partially, of the huge reduction of agrobiodiversity that led to the necessity of making food production systems more diverse, resilient, and environmentally sustainable. Therefore, sustainable use and conservation the widest biodiversity of crops is essential to food security and sustainable agriculture.[4,5]

In line with this, one possible option is to rescue neglected and underutilized crop plants able to grow under less favorable weather conditions that could be suitable to be used as staple crops (Figure 2).

On the other hand, the search for "*new foods for new needs*" in recent years has led to a significant increase in the global food demand for new plant-based products specially those obtained from emerging crops such as ancient cereals, pseudocereals, and pulses which possess high nutritional value. In fact, some of these crops are known as superfoods and this is attributed to their nutritional profiles that, mainly in recent years, have proven results benefiting human and animal health.[6–8]

Nutrients required to sustain basic functions for the human body are obtained from a balanced diet. The nutrients considered essential for human health are mainly grouped in carbohydrates, lipids, proteins, vitamins, minerals, and water. All are contained in a proper balance in quinoa, amaranth, and chia, which therefore constitute nutritious foods for human diets.[9,10] Furthermore, in addition to having a high nutritional value, the seeds of these crops are gluten free, making them suitable and safe for people with celiac disease (a serious genetic autoimmune disease that interferes with the absorption of nutrients and affects the villi of the small intestine due to gluten intolerance)[11] providing starch, fiber, proteins with a balanced amino acid profile, lipids rich in polyunsaturated fatty acids, minerals, and vitamins.[12] Moreover, different plant parts of these crops can be eaten,

although still are mainly consumed their seeds. In addition, they contain other molecules that have health beneficial effects including betalains, phenolic compounds, and phytosterols[6,10,13] and the extracts obtained from these crops have been used to enrich other traditional foods.[14]

The outstanding genetic diversity of these crops gives them an excellent capacity to adapt to different environments[15] which is especially relevant considering the current climate change prospects. This remarkably adaptation capacity is expected to impact on agricultural, environmental sustainability, and food security. Since sustainability is a multi-faceted issue, the food production system, and our diets can play a crucial role minimizing the negative impacts on the environment. Thus, ensuring a sustainable and healthy food future is a task for global cooperation.

Considering the importance of the nutritional properties of quinoa, chia, and amaranth, the purpose of this review is to provide updated information on the nutritional profiles of these emerging crops highlighting the impact on human diet and health.

NUTRITIONAL PROPERTIES OF QUINOA (*CHENOPODIUM QUINOA* WILLD)

Quinoa (*Chenopidium quinoa* Willd.), of the Chenopodiaceae family, is native to the Andes and originated in Peru and Bolivia, around Lake Titicaca. This crop, with a high nutritional density, is considered a complete food. Quinoa has a high protein, vitamins, lipids, fiber, and minerals content and an excellent balance of essential amino acids.[16] In addition, quinoa has been found to contain numerous phytochemicals, including saponins, phytosterols, phytoecdysteroids, phenolic compounds, and bioactive peptides, all with a high functional role, giving them not only nutritional value, but also pharmaceutical and therapeutic roles surpassing traditional cereals such as rice, wheat, corn, and others in nutritional and functional quality[17,18] (Table 1). Quinoa has also been reported to have excellent technological potential, with many options for the creation of new foods, especially for gluten-free alternatives used in formulations.[19]

Proteins and amino acids

Seed protein content is an important trait affecting nutritional quality. The quinoa seed has a high quantity and quality of protein compared to cereal grains. The protein content varies according to the variety analyzed but ranges from 11% to 19%.[20–27]

As mentioned, another interesting fact about quinoa is that its seed is gluten-free, which makes it can be consumed by patients with celiac disease. In addition, quinoa protein has a low prolamin content (0.5%–7.0%), making it low in allergenicity.[28–30]

The amino acid profile also gives quinoa a high nutritional value. In fact, quinoa contains adequate levels of all essential amino acids.[31] It is exceptionally high in essential amino acids lysine, for instance, which is deficient in many cereal grains. Similarly, quinoa seeds are also rich in methionine.[32,33]

TABLE 1 Bioactive compounds and properties of the major phytochemicals identified in quinoa plants (*Chenopodium quinoa* W.).

BIOACTIVE COMPOUNDS		Quinoa (*Chenopodium quinoa*)	HEALTH RELATED BENEFITS[a]
Phenolic compounds	Ferulic acid Vanillic acid Rosmarinic acid Chlorogenic acid		Therapeutic potenctial against cáncer
Flavonoid compounds	Quercetin Kaempferon		Anti-inflammatory
Vitamins	Vitamin A Vitamin B1, B2, B5, B6 and B9 Vitamin C Vitamin E		Anti-obesity
Phytosterols	β-Sitosterol		Cardioprotective effects
Lipids	Linoleic acid α Linolenic acid		Neurodegenerative disorders
Betalains	Betacyanins Betaxanthins		Anti-diabetic properties
Peptides	IQAEGGLT, DKDYPK, GEHGSDGNV		Anti-allergenic activities observed in vitro
Phytoecdysteroids			Low prolamin content
Glycine betaine			Antiviral and antibacterial agents
Saponins			Anti-neoplastic pharmacophor agents
			Low glycemix index
			Improves intestinal microbiota
			High antioxidant capacity
			Anti-lipidemic capacity

[a]To confirm the associated health benefits further studies are required in order to prove their benefits and putative risks.

Carbohydrates and fiber

Carbohydrates represent the largest proportion of macronutrients in quinoa seeds, accounting for 58%–64% of the seed's dry matter (DM). Starch represents the main form of carbohydrate in the seed, consisting of small granules of approximately 1.5 μm in diameter.[34] However, quinoa seeds have a lower carbohydrate content than cereals such as wheat, corn or rice, whose carbohydrate percentages range from 78% to 81% of dry matter.[27] In quinoa, the carbohydrate content varies little between the different varieties of grain, although carbohydrate levels are slightly higher in white and black varieties.[25] Free sugar content in quinoa is generally low, and the main sugars are sucrose, glucose, fructose, arabinose, and maltose.[31] This makes quinoa a species with a low glycemic index: less than 55 on a scale of 0–100 is considered a low glycemic index, and quinoa's varies between 35 and 53, depending on the form of consumption.[25] In contrast, recent studies involving several varieties of quinoa have found that the glycemic index of quinoa averages around 63.[35]

Fiber is the carbohydrate fraction most resistant to enzymatic digestion and absorption by the intestine, where it is partially fermented. Dietary intake of fiber is considered essential for optimal digestive health: fiber induces satiety, lowers cholesterol, and improves intestinal microbiota, among other benefits.[36,37] The total fiber content of quinoa is proportionally higher than that of other cereals, and total, insoluble and soluble fiber levels have been found to range from 14% to 20%, 10% to 14%, and 3.7% to 5.9% respectively.[38] The main components of dietary fiber are non-starch polysaccharides, resistant starch, and non-digestible oligosaccharides.[39] Chemical analysis of the fiber in quinoa seeds has shown that cellulose (52%) and hemicellulose (41%) are the main components, while pectins (4.7%) and lignins (1.7%) are less abundant.[40]

Lipids

The total lipid content of quinoa seeds varies significantly depending on the variety tested, ranging from 2% to 10%.[23] It has been estimated that quinoa oil production would vary between 80 and 400 kg/ha of oil.[41] Therefore, it has been proposed that quinoa could be an alternative oil seed crop.[42] Analysis of the fatty acid profile of quinoa seed has shown that it is rich in unsaturated fatty acids (70.0%–89.4%).[31,43] Curti et al.[41] analyzed the fatty acid profile of quinoa varieties grown at sea level and found that, among the unsaturated fatty acids, the most abundant was linoleic acid (28.3–44.0 g/kg whole seeds), followed by oleic acid (8.6–18.0 g/kg whole seeds) and α-linolenic acid (2.75–5.07 g/kg whole seeds). Among the saturated fatty acids, the most abundant was palmitic acid (5.2–8.4 g/kg whole seeds). In general, these data agree with findings in other studies carried out on quinoa seeds, in which the most abundant unsaturated fatty acid has always been linoleic acid, and the most abundant saturated fatty acid was palmitic acid.[27,44–46] The ratio of unsaturated fatty acids to saturated fatty acids was between 6 and 8. Omega-3 (C18:3, omega-3, α-linolenic acid) and omega-6 (C18:2, omega-6, linoleic acid) fatty acids are considered essential fatty acids, since they are necessary for our health, but our body cannot synthesize them. Our diet must contain enough of these fatty acids, according to current recommendations, as their deficiency or imbalance can lead to serious metabolic disorders.[31] Quinoa oil has a good omega-6/omega-3 ratio, which is usually about 6/1.[23]

Phytosterols

In recent years, phytosterols have become increasingly important because they have been shown to lower blood levels of low-density lipoprotein (LDL) cholesterol and help preventing heart diseases.[47] Chen et al.[43] observed that phytosterol levels varied according to the origin of the quinoa oil tested, with some varieties exceeding 45.0 mg/g of oil. The same study showed that the most abundant phytosterol was β-sitosterol (19.6–46.6 mg/g), followed by stigmasterol (8.7–20.1 mg/g), and campesterol (0.4–2.0 mg/g). However, when the phytosterol content of whole quinoa flour was analyzed, its concentration was approximately 0.80 mg/g; once again, β-sitosterol was the most abundant phytosterol.[48]

Vitamins

The intake of vitamins in the diet is essential for human health. The main sources of vitamins in human diet are usually vegetables and fruits. Quinoa seed can be an important source of vitamins, as it is rich in a significant number of them,[16,23] including the following: riboflavin (vitamin B2, 0.32–0.39 mg/100 g), thiamin (vitamin B1, 0.36–0.40 mg/100 g), panthothenic acid (vitamin B5, 0.61 mg/100 g), pyrodoxine (vitamin B6, 0.20 mg/100 g), and folic acid (vitamin B9, 23.50–78.10 mg/100 g). They also contain vitamin A (14.50 mg/100 g), ascorbic acid (vitamin C, 4.00–16.40 mg/100 g), and tocopherol (vitamin E, 1.73–5.37 mg/100 g). Besides, quinoa seeds contain different tocopherol isoforms: the most abundant is γ-tocopherol (47–53 μg/g), followed by α-tocopherol (17–26 μg/g) and finally δ- and β-tocopherol (<5 μg/g).[16]

Minerals

The ash content of quinoa seeds is high (2.4%–4.8%) compared to cereal grains such as wheat (1.8%) or rice (0.5%).[16,26] Quinoa is a good source of several minerals, including the micronutrients calcium, manganese, magnesium, phosphorus, iron, and copper. The mineral content can change depending on several variables, including climate, soil, quinoa variety, and the fertilizer application.[49] According to Angeliet al.[26] the concentrations of calcium (514–1274 mg/kg), phosphorus (1400–5270 mg/kg), iron (14–168 mg/kg), magnesium (1741–5020 mg/kg), zinc (21.5–48.0 mg/kg), copper (2–51 mg/kg), and potassium (6490–14,678 mg/kg) vary widely in their seeds, although they are always present in sufficient quantities for the human diet.

It should be noted that a balanced mineral intake is crucial for human health. Low dietary mineral intake can cause a number of different adverse health effects. For example, low intakes of micronutrients such as zinc, iron, and copper have been found to be associated with increased depression.[50] Zinc deficiency, which affects a significant number of people in developing countries, can lead to growth retardation, hypogonadism, immune system dysfunction, and cognitive impairment. It is mainly associated with deficient zinc absorption mediated by complexation due to the high phytate content of the cereals consumed in these countries.[51] In this regard, quinoa constitutes a good mineral source as their general content appears in greater concentrations in most part of cereal grains.

Polyphenols

Polyphenols are possibly one of the most studied functional phytochemicals. They have been shown to have a broad bioactivity and high antioxidant capacity, and their consumption has been found to favor hypocholesteremia, immunostimulating, and antihypertensive effects.[52] Polyphenols are mainly classified into two main groups: flavonoids and phenolic acids. The flavonoids are further divided into flavones, flavonones, flavanols, flavonols, and isoflavones, while the phenolic acids are classified into hydroxybenzoic and hydroxycinnamic acids. Analyzing the phenolic content of different varieties of quinoa (white, red, and black), Tang et al.[53] observed the presence of 23 phenolic compounds, most of which were phenolic acids; the most abundant phenolic acids were ferulic acid and vanillic acid and their derivatives. The most abundant flavonoids were quercetin and kaempferol and their glycosides. The total phenolic compound content in quinoa may vary depending on the variety, as well as on other factors like the climatic conditions and type of fertilization used.[54] Han et al.[55] observed that dark quinoa varieties, for instance,

contained higher levels of ferulic acid and gallic acid in both, free and bound forms.

In some cases, quinoa seeds need to be processed for consumption (for instance, when saponins are present in large amounts), and also different cooking methods can be used, both significantly affecting the polyphenol content. Gu et al.[56] observed that steaming had the greatest effect on phenolic compounds, leading to a significant loss of phenolic/flavonoid compounds, thus reducing their antioxidant capacity. However, germination methods have been found to increase the levels of phenolic compounds.

Betalains

Betalains are water-soluble plant pigments that are characteristic of plants belonging to the order Caryophyllales, to which quinoa belongs. However, few studies have been carried out on the betalain composition of quinoa seeds.[57] The analysis of quinoa seeds of different varieties has made it possible to identify betalains as the main factor responsible for their color: the pigment betanin and its isomer isobetanin are responsible for the red-violet varieties and the betaxanthins for yellow-orange pigmentation.[13,53] Interestingly, in recent years, the ability of betalains to act as free radical's scavengers has also been proposed.[13]

Glycine betaine

Glycine betaine is a quaternary ammonium compound synthesized in bacteria, marine invertebrates, plants, and mammals.[58] Glycine betaine is accumulated as osmoprotectan in plants exposed to different stresses such as salinity, drought, heavy metals, heat, and cold stress.[59] Glycine betaine synthesis mainly occurs in halophyte species, and only a few crop plants synthetize and accumulate this compound. Quinoa, a halophyte, belongs to the Amaranthaceae family, as do many halophyte species. Quinoa seeds contain a high concentration of glycine betaine (3930–6000 μg/g DM) in comparison to cereals and cereal-like crops, such as raw grain wheat (1150–1320 μg/g DM), oats (280–388 μg/g DM), rye (1530–1760 μg/g DM), or barley (460–980 μg/g DM).[60–62]

Playing a critical role in human metabolism, glycine betaine functions as a methyl donor and as an osmolyte, mainly in the kidney and liver. Glycine betaine is also involved in the regulation of plasmatic homocysteine, reducing its concentration and decreasing vascular disease risk.[60] Although our bodies synthesize glycine betaine, we need an additional supply in our diet. Cereal foods are the main sources of glycine betaine in western Europe, accounting for 60%–67% of the total glycine betaine ingested.[61] However, people with celiac disease cannot consume these foods due to the presence of gluten. It has been therefore proposed that the consumption of the quinoa seed, given its high levels of glycine betaine, could be a suitable supplement to replace glycine betaine intake from other cereals.

Anti-nutritional components

The main component with anti-nutritional capacity in the quinoa seeds is phytic acid. Phytic acid (myoinositol 1,2,3,4,5,6-hexakis dihydrogen phosphate) is mainly found in cereals and legumes, and constitutes a form of phosphorus storage in many plant species.

Phytic acid is mainly found in the outer layers of grains and seeds of most cereals and legumes in concentrations that ranged between 1% and 3% of the total dry matter. In quinoa seeds, the phytic acid is located in the external layers as well as in the endosperm. Phytic acid levels in quinoa are generally low, ranging from 1.0 to 1.3 g/100 g.[63–65] Different studies have demonstrated that phytic acid inhibits mineral uptake in the human gut because it binds minerals to form insoluble complexes with divalent cations such as zinc, iron, and calcium.[66] It has been observed that the fermentation process can significantly degrade the phytate content in quinoa flour and to a lesser extent in the quinoa seed.[67]

Saponins are natural detergents found in many plant species. These compounds have a skeleton derived from the 30-carbon precursor oxidosqualene to which glycosyl residues are attached. Saponins are described as natural protectants in plants against microbial infections and bird/insect attacks.[68] The quinoa seeds contain saponins, which are mainly located in the pericarp and on the basis of its saponin content quinoa can be classified as sweet, when saponin levels are below 0.11%, or bitter, when the levels are above 0.11%.[63] Saponin accumulation increases the bitterness of quinoa, influencing its taste and digestibility. For this reason, one of the objetives of certain quinoa breeding programs is to obtain sweet varieties by reducing the saponin content in seeds to avoid the process of scarification which may reduce its productivity and marketing affecting its nutritional quality.[31,69]

Recently, however, the pharmacological activities of saponins have been reported, including their role as antioxidants, potent antineoplastic pharmacophores, and antiviral/antibacterial agents.[70]

NUTRITIONAL PROPERTIES OF AMARANTHUS (KIWICHA (*AMARANTHUS CAUDATUS* L.), AMARANTH (*AMARANTHUS CRUENTUS* L.), AND AMARANTH (*AMARANTHUS HYPOCHONDRIACUS* L.))

Amaranthus spp. has been a source of nutritious food for many centuries in Africa, Asia, Mesoamerica, and South America. About 60 species were native to the Americas and a total of about 15 others to Europe, Asia, Africa, and Australia.[71,72] *A. caudatus*, *A. cruentus*, and *A. hypochondriacus* are the main species cultivated due to the characteristics of their seeds. Generally, amaranth is an underutilized crop with high nutritional quality and is considered an alternative crop for sustainable food production. Amaranth is a potential source of high quality protein (which includes an outstanding balance of essential amino acids), dietary fiber and lipids rich in unsaturated fatty acids, also with desirable levels of minerals, vitamins, in addition to other

TABLE 2 Bioactive compounds and properties of the major phytochemical identified in three species of amaranth (*Amaranthus caudatus* L., *Amaranthus cruentus* L., and *Amaranthus hypochondriacus* L.).

BIOACTIVE COMPOUNDS			HEALTH RELATED BENEFITS[a]
Phenolic compounds	Ferulic acid Gallic acid Hydroxybenzoic acid	Amaranth (*Amaranthus* L.)	Hypoglucemic Anti-diabetic activity Activates immune system Anti-neoplasic pharmacophores Cardioprotective/ Regulates arterial pressure Anti-hypercholesterolemic/ anti-Atherogenic Anti-hyperlipidemic Antioxidant activity Antiviral and antibacterial agents
Flavonoid compounds	Quercetin Rutin Kaempferol Isorhamnetin		
Vitamins	Vitamin B1, B2, B3, B6 and B9 Vitamin E		
Phytosterols	Spinasterol Sitosterol		
Lipids	Linoleic acid α Linolenic acid		
Betalains	Amaranthin Isoamaranthin		
Peptides	YP, LPP, GGEDE		
Glycine betaine			
Saponins			

[a]To confirm the associated health benefits further studies are required in order to prove their benefits and putative risks.

bioactive components such as phytosterols, squalene, saponins, polyphenols, and others (Table 2). Amaranth is currently in demand by specific consumers, such as people with diabetes and coeliac disease.[73–75]

Proteins and amino acids

The protein of amaranth is of an unusual high quality due to its outstanding balance and high levels of essential amino acids. The protein content of amaranth can vary, depending on the species analyzed, between 13% and 19%.[71,76,77] It thus has higher protein contents than maize, wheat or rice, although the amount is similar to that found in quinoa and slightly lower than that found in chia. Aguilar et al.[78] observed that *A. cruentus* contained between 13.20% and 15.07% protein depending on the variety, while *A. hypochondriacus* contained 16.20%. According to several authors, the most abundant proteins in amaranth seeds are albumin (65%), globulin (17%), prolamin (11%), and glutelin (7%). For example, the levels of tryptophan and lysine in amaranth seeds are higher than those found in rice, wheat and maize. *A. caudatus* is characterized by having higher levels of lysine (4.8–6.7 g/100 g protein), isoleucine (3.6–5.2 g/100 g protein), threonine (3.3–5.1 g/100 g protein), tryptophan (1.1–1.8 g/100 g protein), and sulfur amino acids (4.5–4.9 g/100 g protein) than other amaranth species.[71]

Carbohydrates and fiber

The carbohydrate content of amaranth is high at approximately 65–75 g/100 g of dry seeds.[79] Starch is the main component of the amaranth seed, accounting for 48%–65% of the total dry weight. The starch grain is polygonal and 1–3 microns in size.[80] Studies in *A. hybridus* and *A. hypochondriacus* show that the main component is branched amylopectin. The main sugar present in the *A. cruentus* seed is sucrose, at 0.58–2.26 g/100 g DM.[81,82] Other sugars present in *A. cruentrus* and *A. caudatus* are fructose (0.12–0.17 g/100 g DM), glucose (0.34–0.42 g/100 g DM), inositol (0.02–0.04 g/100 g DM), maltose (0.24–0.28 g/100 g DM), and raffinose (0.39–0.48 g/100 g DM).[83,84] On the other hand, the fiber content varies between 2.2% and 8.1% with the soluble dietary fiber fraction representing 14% of the total fiber content.[79]

Lipids

The lipid content in amaranth seeds ranges from 5% to 13%.[84] Amaranth has high quality lipids that contain significant levels of polyunsaturated fatty acids. Tang et al.[85] have analyzed the fatty acid content in different varieties and species of amaranth grown in Ontario (Canada). The total polyunsaturated fatty acid content was 72.09%. The most abundant fatty acid in all the varieties and species analyzed was linoleic acid (omega-6), which represented 43.9%–44.1% of the lipid content in *Amaranthus* spp., 37.1%–45.8% in *A. cruentus* and 44.3%–45.9% in *A. hypochondriacus*. On the other hand, α-linolenic acid (omega-3), showed levels of range 0.64%–0.70% in *Amaranthus* spp., 0.65%–1.33% in *A. cruentus*, and 0.81%–1.40% in *A. hypochondriacus*; these levels are lower than those observed in quinoa.

Among the saturated fatty acids, the most abundant was palmitic acid, whose contents varied between 18.9%–19.3% in *Amaranthus* spp., 19.0%–20.2% in *A. cruentus*, and 18.8%–19.0% in *A. hypochondriacus*. Other authors such as Ayorinde et al.[86] have obtained similar results, noting that polyunsaturated fatty acids represented 73% of the total fatty acids, and that linoleic acid (omega-6) was the most abundant ranging 44.5%–47.8%.[44,87] Calculations of the omega-6/omega-3 ratio in amaranth oil usually range between 5.9 and 69, which indicates that the quality of the oil is significantly lower than that of other pseudocereals such as quinoa or chia.[44,85,87]

Phytosterols

As mentioned previously, clinical studies consistently indicate that the intake of bioactive compounds "phytosterols" is associated with a significant reduction in the levels of low-density lipoprotein cholesterol (LDL-cholesterol) and cardiovascular disease.[88,89]

The phytosterol content in amaranth seeds is higher than in many vegetables and fruits.[90] Analysis of the different phytosterols present in amaranth seeds shows that the most abundant are sitosterol and spinasterol, whose concentrations vary according to the amaranth species analyzed.[90–92] Berger et al.[91] found that amaranth oil contained a phytosterol concentration of 2.73 g/100 g and that spinasterol and sitosterol were the most abundant (34.2%, both compounds

coelute). Similarly, Ogrodowska et al.[92] and Marcone et al.[90] also observed that both of these compounds were the most abundant phytosterols in amaranth seeds (55–100 mg/100 g of seeds).

Vitamins

Amaranth seeds are not different from those of cereals in terms of vitamin composition. The vitamin contents of *A. caudatus* are in the following ranges: thiamin (vitamin B1, 0.072–0.240 mg/100 g), riboflavin (vitamin B2, 0.18–2.70 mg/100 g), nicotinamide (vitamin B3, 0.89–1.00 mg/100 g), pirodoxin (vitamin B6, 0.59 mg/100 g), and folic acid (vitamin B9, 0.08 mg/100 g). Amaranth seeds also contain significant amounts of tocopherol (vitamin E) and tocotrienol[79,87,92,93] and accumulate significantly higher amounts of both β- and γ-tocotrienols compared to grain cereals. In *A. cruentus* and *A. hypochondriacus* varieties, the following levels have been detected: α-tocopherol (2.97–15.65 µg/g seed), β-tocotrienol (5.92–11.47 µg/g seed), and γ-tocotrienol (0.95–8.69 µg/g seed). Besides, Ogrodowska et al.[92] observed the following levels of tocopherols in *A. cruentus*: α-tocopherol (19.1 µg/g seed), β-tocopherol (40.7 µg/g seed), γ-tocopherol (12.9 µg/g seed), and δ-tocopherol (33.4 µg/g seed).

Minerals

The ash content in amaranth is found within the range of 2.88%–3.90%.[71,82,92,94,95] The mineral content of both, micronutrients and macronutrients, is affected by agronomical and climatic conditions. Amaranth stands out for having high levels of iron and potassium, which makes it an important source of these minerals for diets low in them. In *Amaranthus caudatus* seeds, the mineral contents are as follows: phosphorus (5600–5800 mg/kg), potassium (4870–5000 mg/kg), magnesium (2800–2900 mg/kg), calcium (1760–1800 mg/kg), iron (90–140 mg/kg), manganese (13.00–33.30 mg/kg), and copper (9.00–12.00 mg/kg).[44,82] In *Amaranthus cruentus*, these minerals can be found in the following ranges: phosphorus (560–6000 mg/kg), potassium (7350–7700 mg/kg), magnesium (3120–4250 mg/kg), calcium (2000–2830 mg/kg), iron (1.4–2.9 mg/kg), manganese (24–41 mg/kg), and copper (9.00–12.50 mg/kg).[82,87]

Polyphenols

As mentioned above, polyphenols play a very relevant role in human nutrition given their high antioxidant capacity, reducing the risk of cardiovascular diseases and also, chronic inflammation. Bioactive phytochemicals are mainly located in the seed coat of amaranth seeds, functioning as a chemical defense against insects and microorganisms. The total concentrations of phenolic acids found in amaranth seeds range between 168–329 mg/kg, with the extractable fraction of phenols ranging between 7% and 14%.[84] The most abundant free phenolic acids in amaranth seeds are gallic acid (11–440 mg/kg dry seed), ferulic acid (120–620 mg/kg dry seed), and p-hydroxybenzoic acid (8.5–20.9 mg/kg dry seed).[71,84,96] On the other hand, the most abundant flavonoids are quercetin (214–843 mg/kg dry seed) and rutin (7–592 mg/kg dry seed).[84]

Betalains

Betalains are other phytochemicals that have been identified in *A. caudatus*, mainly betacyanins and betaxanthins, which are a type of indole-derived pigments with a red and yellow color that is used as a natural food colorant, but also acts as an efficient scavenger of reactive oxygen species (ROS) and in the antioxidant capacity/activity of defense mechanisms.[97] The main betalains identified in *A. caudatus* are amaranthin (151.3 mg/kg) and isoamaranthin (58.7 mg/kg).[84]

NUTRITIONAL PROPERTIES OF CHIA (*SALVIA HISPÁNICA* L.)

Chia (*Salvia hispánica* L.), of the Lamiaceae family, is native to the central valleys of Mexico and northern Guatemala[98,99] and was one of the main staple crops of pre-Columbian societies, who used the seeds for the preparation of various medicines, foods, and paintings.[100,101] Chia seeds are a good source of minerals and vitamins, as well as bioactive compounds with high antioxidant activity, particularly polyphenols and tocopherols, and show a high content of dietary fiber and proteins[30] (rich in many essential amino acids) (Table 3).

Proteins and amino acids

Chia seeds have high protein contents, varying between 16% and 24% depending on their origin,[9,99,102–104] and high levels of certain amino acids such as aspartic and glutamic acid, serine, alanine, and glycine.[105] Regarding the free amino acid content, at least 10 amino acids are present in chia seeds, and the most abundant are arginine, leucine,

TABLE 3 Bioactive compounds and properties of the major phytochemical identified in chia plants (*Salvia hispánica* L.).

BIOACTIVE COMPOUNDS			HEALTH RELATED BENEFITS[a]
Phenolic compounds	Rosmarinic acid Protocatechuic ethyl ester Caffeic acid Gallic acid Salviaflaside	Chia (*Salvia hispanica*)	Hypotensive effeccts Hypoglycaemic effects Immunostimulatory effects Anti-inflammatory effects Cardioprotective effects Antioxidant activity Anti-lipidemic effects Antimicrobial Activitiestherapeutic potenctial against cáncer
Flavonoid compounds	Methylquercetin Daidzin		
Phytosterols	β-Sitosterol Stigmasterol Campesterol		
Lipids	α-Linoleic acid Linoleic acid		
Vitamins	Vitamin B1, B2 and B3 Vitamin C Vitamin E		

[a]To confirm the associated health benefits further studies are required in order to prove their benefits and putative risks.

phenylalanine, lysine, and valine.[103] Due to the physico-chemical characteristics of chia proteins, such as their high emulsifying capacity, good foam stability and viscosity, chia proteins are a very promising food additive for improving food quality as well as for increasing the shelf life of certain foods.[103] In fact, the use of chia flour has significantly risen in recent years, and it has also proven to be valuable in the elaboration of gluten-free products.

Carbohydrates and fiber

The carbohydrate content in chia varies significantly depending on the seed origin, ranging from 26.9% to 42.1%.[9,106] The dietary fiber content can vary from 30.2% to 34.4%, and the ingestion of 100 g of chia seeds meets in more than 100% the recommended fiber dietary intake.[9,104] From the total fiber content found in chia, the insoluble fraction accounts for 85%–93%, while the soluble fraction accounts for 7%–15%.[11,107] Interestingly, the dietary fiber content in chia is higher than that found in crops, such as quinoa (7.0 g/100 g), amaranth (6.7 g/100 g), peanuts (8.5 g/100 g), and soybean (9.6 g/100 g). It is also known that defatted chia flour contains 40% fiber, and 5%–10% is soluble fiber, which is part of the mucilage.[108]

Lipids

The chia seed is highly rich in lipids: the total lipid content is between 27.5% and 40.2%.[9,102–104,106,109] The fatty acid profile is of great interest, as it is quite rich in polyunsaturated fatty acids. Researchers have found that the main constituent in chia oil is α-linolenic acid (omega-3), which ranges from 45.3% to 64.8%, followed by and linoleic acid (15.3%–22.5%).[9,28,95,98] Ayerza and Coates[102] showed that α-linolenic acid levels were affected by the growing conditions, varying from 56.9% to 64.8%. Other saturated and monounsaturated fatty acids have been found in lower amounts including palmitic acid (5.10%–8.53%) and oleic acid (7.3%–18.1%). The ratio of omega-3/omega-6 founding chia is optimal, varying between 3.0 and 3.8, which possess important health benefits.

Phytosterol

Chia seed contains an unusually high content of phytosterols and have been associated with a wide range of physiological functions in human health. These compounds have been shown to have cardiac, anti-inflammatory, control of diabetes, hypertension, and antioxidant effects.[108] Ciftci et al.[110] have shown that chia seed lipids contain phytosterols (4.13 g/kg of lipids), mainly campesterol (0.47 g/kg of lipids), stigmasterol (1.25 g/kg of lipids), and β-sitosterol (2.06 g/kg of lipids). Rokosik et al.[111] have obtained similar results from cold-pressed chia oil: out of the 4.55 g/kg phytosterols detected, the most abundant was β-sitosterol (2.16 g/kg of lipids), followed by stigmasterol (1.99 g/kg of lipids) and campesterol (0.40 g/kg of lipids).

Vitamins

Chia seeds can be considered a good source of B vitamins. Ranging between 6.1 and 8.8 mg/100 g, its niacin (vitamin B3) levels are high compared to those found in other grains or seeds such as corn, soybeans, or rice.[9,101] The concentrations of thiamin (vitamin B1, 0.18–0.60 mg/100 g) and riboflavin (vitamin B2, 0.04–0.20 mg/100 g) in chia are similar to those found in rice and maize, although lower than those of soybean and safflower.[9,101,108] The levels of other vitamins, such as vitamin C (1.6 mg/100 g), vitamin A (44 IU), and folate (49 µg/100 g), are relatively low compared to other grains and seeds.[9] The levels of vitamin E have been found to vary between 0.5 and 8.2 mg/100 g.[112,113] A study in rats showed that a chia-rich diet significantly increased vitamin B12 levels, suggesting that chia may be a good additive for vegan diets where vitamin B12 levels may be low.[114]

Minerals

The ash content of chia seeds (between 2.79% and 4.80%) is high compared to that of other grains and seeds such as rice, amaranth, or quinoa.[9,104,112] Chia seed is very rich in phosphorus (4930–8600 mg/kg), potassium (4070–8630 mg/kg), calcium (2970–6310 mg/kg), magnesium (1950–3500 mg/kg), iron (25–164 mg/kg), zinc (26–47 mg/kg), and copper (4.1–13.2 mg/kg). Da Silva et al.[112] have shown that the mineral content can be affected by the cultivation location and climatic conditions. A comparison of the calcium and magnesium content in chia versus that in cow's milk (100–140 mg Ca/100 ml, 10–15 mg Mg/100 ml),[115] showed that chia contains six times more calcium and 20 times more magnesium, highlighting the outstanding role as a mineral source when incorporated in our diets.

Polyphenols

Pigni et al.[116] have analyzed the polyphenol contents in the meal obtained after oil extraction from chia seeds. Analysis of the polyphenol profile identified 14 compounds, of which 12 were hydroxycinnamic acid derivatives; the other two were quinic acid and the flavonoid methylquercetin. Ten of the hydrocinnamic acid-derived compounds were related to caffeic acid, while the remaining two were related to ferulic and fertaric acid. However, the two most abundant compounds, up to 10 times more abundant than the rest, were rosmarinic acid (33.97 mg/100 g) and its glycosylated derivative (Salviaflaside, 30.69 mg/100 g). Other authors have obtained similar results, identifying 29 different phenolic acids and showing that hydroxycinnamic acids and their derivatives are the most represented.[117] On the other hand, Martinez-Cruz et al.[118] observed that the most abundant phenolic compounds in chia seeds were rosmarinic acid 0.92, protocatechuic ethyl ester 0.74, caffeic acid 0.02, gallic acid 0.01, and daidzin 0.006 mg/g seed.

CONCLUSION

One of the most important impacts of climate change is its effect on agriculture and food safety, and, as a result, on human nutrition.

This fact highlights the urgent need of establishing new alternative nutritious crops, environmentally sustainable, able to contribute to improve our diet, ensuring food security and food quality.

Current research has indicated that some of the compounds found in emerging crops, such as quinoa, amaranth, and chia, could provide beneficial effects linked not only to their nutritional properties, but also due to their pharmaceutical and therapeutic effects. This review has described the most recent information regarding the compositional profiles of their seeds which will contribute to establishing these emergent crops as healthy foods for developing functional products. Due to more vegan and vegetarian diets, an increasing use of vegetable protein has been required to support the production of protein-rich foods which can replace animal proteins in the human diet. Amaranth, chia, and quinoa seeds contain proteins which have biological and functional properties that provide high nutritional benefits due to their reasonably well-balanced amino acid content. In summary, these seeds are also rich in unsaturated fatty acids (Omega-3, omega-6), vitamins (A, B1, B2, B5, B6, B9, B12, E), polyphenols, glycine-betaine, and with mineral content rich in calcium, phosphorus, iron, and potassium.

Currently, these nutritional, pharmaceutical, and therapeutic characteristics alone consolidate quinoa, amaranthus, and chia as versatile future food crops that could eventually become staple foods in the twenty-first century.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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REFERENCES

1. FAO. The impact of disasters and crises on agriculture and food security: 2021. Rome. 2021. https://doi.org/10.4060/cb3673en
2. Kew RBG. The state of the World's plants report. Kew: Royal Botanic Gardens; 2016.
3. N'Danikou S, Tchokponhoue DA. Plant domestication for enhanced food security. In: Filho LW, Azul A, Brandli L, Özuyar P, Wall T, editors. Zero hunger. Encyclopedia of the UN sustainable development goals. Cham: Springer; 2019. https://doi.org/10.1007/978-3-319-69626-3_96-1
4. Pichop GN, Abukutsa-Onyango M, Noorani A, Nono-Womdim R. Importance of indigenous food crops in tropical Africa: case study. Acta Hortic. 2016;1128:315–22. https://doi.org/10.17660/ActaHortic.2016.1128.47
5. Ulian T, Diazgranados M, Pironon S, Padulosi S, Liu U, Davies L, et al. Unlocking plant resources to support food security and promote sustainable agriculture. Plants People Planet. 2020;2:421–45. https://doi.org/10.1002/ppp3.10145
6. Hernández-Ledesma B. Quinoa (*Chenopodium quinoa* Willd.) as a source of nutrients and bioactive compounds. Bioact Compd Health Dis. 2019;2(3):27–47. https://doi.org/10.31989/bchd.v2i3.556
7. Singh B, Singh JP. Bioactive constituents in pulses and their health benefits. J Food Sci Technol. 2017;54(4):858–70. https://doi.org/10.1007/s13197-016-2391-9
8. Zamaratskaia G, Gerhardt K, Wendin K. Biochemical characteristics and potential applications of ancient cereals - an underexploited opportunity for sustainable production and consumption. Trends Food Sci Technol. 2021;107:114–23. https://doi.org/10.1016/j.tifs.2020.12.006
9. Kulczynski B, Kobus-Cisowska J, Taczanowski M, Kmiecik D, Gramza-Michałowska A. The chemical composition and nutritional value of Chia seeds: current state of knowledge. Nutrients. 2019;11(6):1242. https://doi.org/10.3390/nu11061242
10. Martínez-Villaluenga C, Peñas E, Hernández-Ledesma B. Pseudocereal grains: nutritional value, health benefits and current applications for the development of gluten-free foods. Food Chem Toxicol. 2020;137:11178. https://doi.org/10.1016/j.fct.2020.111178
11. Woomer JS, Adedeji AA. Current applications of gluten-free grains – a review. Crit Rev Food Sci Nutr. 2021;61(1):14–24. https://doi.org/10.1080/10408398.2020.1713724
12. Haros CM, Schoenlechner R. Food uses of whole Pseudocereals. Pseudocereals: chemistry and technology. Hoboken, NJ, USA: John Wiley & Sons; 2017. p. 163–92.
13. Escribano J, Cabanes J, Jimenez-Atienza M, Ibañez-Tremolada M, et al. Characterization of betalains, saponins and antioxidant power in differently colored quinoa (*Chenopodium quinoa*) varieties. Food Chem. 2017;234:285–94. https://doi.org/10.1016/j.foodchem.2017.04.187
14. Fernández-López J, Viuda-Martos M, Sayas-Barberá ME, Navarro-Rodríguez de Vera C, Lucas-González R, Roldán-Verdú A, et al. Chia, Quinoa, and their coproducts as potential antioxidants for the meat industry. Plan Theory. 2020;9:1359. https://doi.org/10.3390/plants9101359
15. FAO. The future of food and agriculture – trends and challenges. Vol 11. Rome: FAO; 2017. https://doi.org/10.3390/su11010222
16. Mohamed-Ahmed IA, Al Juhaimi F, Özcan MM. Insights into the nutritional value and bioactive properties of quinoa (*Chenopodium quinoa*): past, present and future prospective. Int J Food Sci. 2021;56:3726–41. https://doi.org/10.1111/ijfs.15011
17. Ren G, Zhu Y, Shi Z, Li J. Detection of lunasin in quinoa (*Chenopodium quinoa* Willd.) and the in vitro evaluation of its antioxidant and anti-inflammatory activities. J Sci Food Agric. 2017;97(12):4110–6. https://doi.org/10.1002/jsfa.8278
18. Stikic RI, Milincic DD, Kostic AZ, Jovanovic ZB, et al. Polyphenolic profiles, antioxidant, and in vitro anticancer activities of the seeds of Puno and Titicaca quinoa cultivars. Cereal Chem. 2020;97(3):626–33.
19. Fernández-López J, Viuda-Martos M, Pérez-Alvarez JA. Quinoa and chia products as ingredients for healthier processed meat products: technological strategies for their application and effects on the final product. Curr Opin Food Sci. 2021;40:26–32. https://doi.org/10.1016/j.cofs.2020.05.004
20. Gesinski K, Nowak K. Comparative analysis of the biological value of protein of *Chenopodium quinoa* Willd. And *Chenopodium álbum* L. part I amino acid composition of the seed protein. Acta Sci Pol Agri. 2011;10:47–56.
21. Miranda M, Vega-Galvez A, Martínez E, López J, Rodríguez MJ, et al. Genetic diversity and comparison of physicochemical and nutritional characteristics of six quinoa (*Chenopodium quinoa* Willd.) genotypes cultivated in Chile. J Food Sci Technol. 2012;32:835–43. https://doi.org/10.1590/S0101-20612012005000114

22. Escuredo O, Martín MIG, Moncada GW, Fisher S, Hierro JMH. Amino acid profile of the quinoa (*Chenopodium quinoa* Willd.) using near infrared spectroscopy and chemometric techniques. J Cereal Sci. 2014;60:67–74. https://doi.org/10.1016/j.jcs.2014.01.016
23. Graf BL, Rojas-Silva P, Rojo LE, Delatorre-Herrera J, Baldeón ME, Raskin I. Innovations in health value and functional food development of quinoa (*Chenopodium quinoa* Willd.). Compr Rev Food Sci Food Saf. 2015;14(4):431–55. https://doi.org/10.1111/1541-4337.12135
24. Reguera M, Conesa CM, Gil-Gomez A, Haros CM, et al. The impact of different agroecological conditions on the nutritional composition of quinoa seeds. PeerJ. 2018;6:e4442. https://peerj.com/articles/4442/
25. Pereira E, Encina-Zelada C, Barros L, Gonzales-Barron U, Cadavez V, C.F.R. Ferreira I. Chemical and nutritional characterization of *Chenopodium quinoa* Willd (quinoa) grains: a good alternative to nutritious food. Food Chem. 2019;280:110–4. https://doi.org/10.1016/j.foodchem.2018.12.068
26. Angeli V, Silva MP, Massuela CD, Khan MW, et al. Quinoa (*Chenopodium quinoa* Willd.): an overview of the potentials of the "Golden grain" and socio-economic and environmental aspects of its cultivation and marketization. Foods. 2020;9:216. https://doi.org/10.3390/foods9020216
27. Sampaio SL, Fernandes A, Pereira C, Calhelha RC, Sokovic M, Santos-Buelga C, et al. Nutritional value, physicochemical characterization and bioactive properties of the Brazilian quinoa BRS Piabiru. Food Funct. 2020;11:2969–77. https://doi.org/10.1039/D0FO00055H
28. Langenkämper G, Zörb C. Modern aspects of wheat grain proteins. J Appl Bot Food Qual. 2019;92:240–5. https://doi.org/10.5073/JABFQ.2019.092.033
29. Bhathal SK, Kaur N, Gill JPS. Effect of processing on the nutritional composition of quinoa (*Chenopodium quinoa* Willd.). Agric Res J. 2017;54:90–9. https://doi.org/10.5958/2395-146X.2017.00015.1
30. Orona-Tamayo D, Valverde ME, Paredes-López O. Bioactive peptides from selected Latin America crops – a nutraceutical and molecular approach. Crit Rev Food Sci Nutr. 2019;59(12):1949–75. https://doi.org/10.1080/10408398.2018.1434480
31. Bastidas EG, Roura R, Rizzolo DAD, Massanés T, Gomis R. Quinoa (*Chenopodium quinoa* Willd), from nutritional value to potential health benefits: an integrative review. J Nutr Food Sci. 2016;6(3):1–10. https://doi.org/10.4172/2155-9600.1000497
32. Ranhotra GS, Gelroth JA, Glaser BK, Lorenz KJ, Johnson DL. Composition and protein nutritional quality of Quinoa. Cereal Chem. 1993;70:303–5.
33. Valencia-Chamorro SA. The world of food grain. Encyclopedia of food grains. Second ed. Oxford: Elsevier; 2016.
34. Lindeboom N, Chang PR, Falk KC, Tyler RT. Characteristics of starch from eight quinoa lines. Cereal Chem. 2005;82:216–22. https://doi.org/10.1094/CC-82-0216
35. Priyanka M, Suneetha WJ, Maheswari KU, Suneetha KB, Kumari BA. Glycemic index profiling of quinoa (*Chenopodium quinoa* Willd) variety. J Pharm Res Int. 2018;21:37915–5. https://doi.org/10.9734/JPRI/2018/37915
36. Ciudad-Mulero M, Fernández-Ruiz V, Matallana-González MC, Morales P. Chapter two - dietary fiber sources and human benefits: the case study of cereal and pseudocereals. Adv Food Nutr Res. 2019;90:83–134. https://doi.org/10.1016/bs.afnr.2019.02.002
37. Zhu F. Dietary fiber polysaccharides of amaranth, buckwheat and quinoa grains: a review of chemical structure, biological functions and food uses. Carbohydr Polym. 2020;248:116819. https://doi.org/10.1016/j.carbpol.2020.116819
38. Sobota A, Świeca M, Gęsiński K, Wirkijowska A, Bochnak J. Yellow-coated quinoa (*Chenopodium quinoa* Willd) – physicochemical, nutritional, and antioxidant properties. J Sci Food Agric. 2020;100:2035–42. https://doi.org/10.1002/jsfa.10222
39. Phillips KM, Haytowitz DB, Pehrsson PR. Implications of two different methods for analyzing total dietary fiber in foods for food composition databases. J Food Compos Anal. 2019;84:103253. https://doi.org/10.1016/j.jfca.2019.103253
40. Zhang D, Wang L, Tan B, Zhang W. Dietary fibre extracted from different types of whole grains and beans. Int J Food Sci. 2020;55:2188–96. https://doi.org/10.1111/ijfs.14472
41. Curti RN, Sanahuja MD, Vidueiros SM, Curti CA, et al. Oil quality in sea-level quinoa as determined by cultivar-specific responses to temperature and radiation conditions. J Sci Food Agric. 2019;100:1358–61. https://doi.org/10.1002/jsfa.10092
42. Navruz-Varli S, Sanlier N. Nutritional and health benefits of quinoa (*Chenopodium quinoa* Willd). J Cereal Sci. 2016;69:371–6. https://doi.org/10.1016/j.jcs.2016.05.004
43. Chen YS, Aluwi NA, Saunders SR, Ganjyal GM, Medina-Meza IG. Metabolic fingerprinting unveils quinoa oil as a source of bioactive phytochemicals. Food Chem. 2019;286:592–9. https://doi.org/10.1016/j.foodchem.2019.02.016
44. Alvarez-Jubete L, Arendt EK, Gallagher E. Nutritive value and chemical composition of pseudocerelas as gluten-free ingredients. Int J Food Sci Nutr. 2009;60:240–57. https://doi.org/10.1080/09637480902950597
45. Filho AM, Ribeiro P, Da Silva Borges JT, Pinheiro Sant'Ana HM, et al. Quinoa: nutritional, functional, and antinutritional aspects. Crit Rev Food Sci Nutr. 2017;57(8):1618–30. https://doi.org/10.1080/10408398.2014.1001811
46. Vera EP, Alca JJ, Saravia GR, Campioni NC, Alpuy IJ. Comparison of the lipid profile and tocopherol content of four Peruvian quinoas (*Chenopodium quinoa* Willd.) cultivars ('Amarilla de Marangani', 'Blanca de Juli', INIA 415 'Roja Pasankalla', INIA 420 'Negra Collana') during germination. J Cereal Sci. 2019;88:132–7. http://www.fao.org/3/u8480e/u8480e07.htm
47. López-Cervantes J, Sánchez-Machado D, de la Mora-López DS, Sanches-Silva A. Quinoa (*Chenopodium quinoa* Willd.): exploring a superfood from Andean indigenous cultures with potential to reduce cardiovascular disease (CVD) risk markers. Curr. Mol Pharmacol. 2021;14:925–34. https://doi.org/10.2174/1874467214999210111222233
48. Ryan E, Galvin K, O'Connor TP, Maguire AR, O'Brien NM. Phytosterol, squalene, tocopherol content and fatty acid profile of selected seeds, grains, and legumes. Plant Foods Hum Nutr. 2007;62:85–91. https://doi.org/10.1007/s11130-007-0046-8
49. Vega-Gálvez A, Miranda M, Vergara J, Uribe E, Puente L, Martínez EA. Nutrition facts and functional potential of quinoa (*Chenopodium quinoa* Willd.), an ancient Andean grain: a review. J Sci Food Agric. 2010;90(15):2541–7. https://doi.org/10.1002/jsfa.4158
50. Li Z, Wang W, Xin X, Song X, Zhang D. Association of total zinc, iron, copper and selenium intakes with depression in the US adults. J Affect Disord. 2018;228:68–74. https://doi.org/10.1016/j.jad.2017.12.004
51. Prasad AS. Impact of the discovery of human zinc deficiency on health. J Am Coll Nutr. 2009;28:257–65. https://doi.org/10.1080/07315724.2009.10719780
52. Pérez-Gregorio R, Soares S, Mateus N, de Freitas V. Bioactive peptides and dietary polyphenols: two sides of the same coin. Molecules. 2020;25(15):3443. https://doi.org/10.3390/molecules25153443
53. Tang Y, Li X, Zhang B, Chen PX, Liu R, Tsao R. Characterisation of phenolics, betanins and antioxidant activities in seeds of three *Chenopodium quinoa* Willd. Genotypes Food Chem. 2015;166:380–8. https://doi.org/10.1016/j.foodchem.2014.06.018
54. Miranda M, Vega-Galvez A, Lopez J, Parada G, et al. Impact of air-drying temperature on nutritional properties, total phenolic content and antioxidant capacity of quinoa seeds (*Chenopodium quinoa* Willd.). Ind Crop Prod. 2010;32:258–63. https://doi.org/10.1016/j.indcrop.2010.04.019

55. Han Y, Chia J, Zhanga M, Zhanga R, et al. Characterization of saponins and phenolic compounds: antioxidant activity and inhibitory effects on α-glucosidase in different varieties of colored quinoa (*Chenopodium quinoa* Willd). Biosci Biotechnol Biochem. 2019;83:2128–39. https://doi.org/10.1080/09168451.2019.1638756
56. Gu R, Chang X, Bai G, Li X, di Y, Liu X, et al. Effects of household cooking methods on changes of tissue structure, phenolic antioxidant capacity and active component bioaccessibility of quinoa. Food Chem. 2021; 350:129138. https://doi.org/10.1016/j.foodchem.2021.129138
57. Henarejos-Escudero P, Guadarrama-Flores B, Guerrero-Rubio MA, Gomez-Pando LR, et al. Development of betalain producing callus lines from colored quinoa varieties (*Chenopodium quinoa* Willd). J Agric Food Chem. 2018;66:467–74. https://doi.org/10.1021/acs.jafc.7b04642
58. Chen TH, Murata N. Glycinebetaine protects plants against abiotic stress: mechanisms and biotechnological applications. Plant Cell Environ. 2011; 34:1–20. https://doi.org/10.1111/j.1365-3040.2010.02232.x
59. Slama I, Abdelly C, Bouchereau A, Flowers T, Savouré A. Diversity, distribution and roles of osmoprotective compounds accumulated in halophytes under abiotic stress. Ann Bot. 2015;115:433–47. https://doi.org/10.1093/aob/mcu239
60. Ross AB, Zangger A, Guiraud SP. Cereal foods are the major source of betain in the western diet – analysis of betaine and free choline in cereal foods and updated assessments of betaine intake. Food Chem. 2014;145:859–65. https://doi.org/10.1016/j.foodchem.2013.08.122
61. Filipcev B, Kojic J, Krulj J, Bodroza-Solarov IN. Betaine in cereal grains and grain-based products. Foods. 2018;7:49. https://doi.org/10.3390/foods7040049
62. Hefni M, Schaller F, Witthöft MC. Betaine, choline and folate content in different cereal genotypes. J Cereal Sci. 2018;80:72–9. https://doi.org/10.1016/j.jcs.2018.01.013
63. Kozioł MJ. Chemical composition and nutritional evaluation of quinoa (*Chenopodium quinoa* Willd.). J Food Compos Anal. 1992;5:35–68. https://doi.org/10.1016/0889-1575(92)90006-6
64. Egli I, Davidsson L, Juillerat MA, Barclay D, Hurrell RF. The influence of soaking and germination on the phytase activity and phytic acid content of grains and seeds potentially useful for complementary feeding. J Food Sci. 2002;67:3484–8. https://doi.org/10.1111/j.1365-2621.2002.tb09609.x
65. Mattila PH, Pihlava JM, Hellström J, Nurmi M, Eurola M, Mäkinen S, et al. Contents of phytochemicals and antinutritional factors in commercial protein-rich plant products. Food Qual Saf. 2018;2:213–9. https://doi.org/10.1093/fqsafe/fyy021
66. Gupta RK, Gangoliya SS, Singh NK. Reduction of phytic acid and enhancement of bioavailable micronutrients in food grains. J Food Sci Technol. 2015;52:676–84. https://doi.org/10.1007/s13197-013-0978-y
67. Castro-Alba V, Lazarte CE, Perez-Rea D, Carlsson NG, Almgren A, Bergenståhl B, et al. Fermentation of pseudocereals quinoa, canihua, and amaranth to improve mineral accessibility through degradation of phytate. J Sci Food Agric. 2019;99:5239–48. https://doi.org/10.1002/jsfa.9793
68. Hussain M, Debnath B, Qasim M, Bamisile BS, Islam W, Hameed MS, et al. Role of saponins in plant pefense against specialist herbivores. Molecules. 2019;24(11):2067. https://doi.org/10.3390/molecules24112067
69. Arendt EK, Zannini E. Quinoa. Cereal grains for the food and beverage industries. Sawston: Woodhead publishing series in food science. Technology and Nutrition; 2013. p. 409–38. https://doi.org/10.1533/9780857098924.409
70. Biswas T, Dwivedi UN. Plant triterpenoid saponins: biosynthesis, in vitro production, and pharmacological relevance. Protoplasma. 2019; 256(6):1463–86. https://doi.org/10.1007/s00709-019-01411-0
71. Martinez-Lopez A, Millan-Linares MC, Rodriguez-Martin NM, Millan F, Montserrat-de la Paz S. Nutracetical value of kiwicha (*Amaranthus caudatus* L.). J Funct Foods. 2020;65:103735. https://doi.org/10.1016/j.jff.2019.103735
72. Sauer JD. The grain amaranths and their relatives: a revised taxonomic and geographic survey. Ann Mo Bot Gard. 1967;54(2):103–37. https://doi.org/10.2307/2394998
73. Joshi DC, Sood S, Hosahatti R, Kant L, Pattanayak A, Kumar A, et al. From zero to hero: the past, present and future of grain amaranth breeding. Theor Appl Genet. 2018;131:1807–23. https://doi.org/10.1007/s00122-018-3138-y
74. Orona-Tamayo D, Paredes-López O. Amaranth part 1—sustainable crop for the 21st century: food properties and nutraceuticals for improving human health. Sustainable protein sources. London: Academic Press; 2017. p. 239–56. https://doi.org/10.1016/B978-0-12-802778-3.00015-9
75. Repo-Carrasco-Valencia R. Andean indigenous food crops: nutritional value and bioactive compounds. Turku Finlad: University of Turku; 2011.
76. Amaranth BR. In: Caballero B, editor. Encyclopedia of food sciences and nutrition. 2nd ed. Oxford: Academic Press; 2003. p. 166–73. https://doi.org/10.1016/B0-12-227055-X/00036-5
77. Grundy MML, Momanyi DK, Holland C, Kawaka F, Tan S, Salim M, et al. Effects of grain source and processing methods on the nutritional profile and digestibility of grain amaranth. J Funct Foods. 2020;72:72. https://doi.org/10.1016/j.jff.2020.104065
78. Aguilar EG, Albarracín Gde J, Uñates MA, Piola HD, et al. Evaluation of the nutritional quality of the grain protein of new amaranths varieties. Plant Foods Hum Nutr. 2015;70:21–6. https://doi.org/10.1007/s11130-014-0456-3
79. Wolosik K, Markowska A. *Amaranthus Cruentus* taxonomy, botanical description, and review of its seed chemical composition. Nat Prod Commun. 2019;14(5):1–10. https://doi.org/10.1177/1934578X19844141
80. Perez-Rea D, Antezana-Gomez R. The functionality of Pseudocereal starches. In: Sjöö IM, Nilsson L, editors. Starch in food: structure, function and applications. ScienceDirect. 2nd ed. Sawston: Woodhead Publishing; 2018. p. 509–42. https://doi.org/10.1016/B978-0-08-100868-3.00012-3.60
81. Becker R, Wheeler EL, Lorenz K, Stafford AE, et al. A compositional study of amaranth grain. J Food Sci. 1981;46:1175–80. https://doi.org/10.1111/j.1365-2621.1981.tb03018.x
82. Gamel TH, Linssen JP, Mesallam AS, Damir AA, Shekib LA. Effect of seed treatments on the chemical composition of two amaranth species: oil, sugars, fibres, minerals and vitamins. J Sci Food Agric. 2006; 86:82–9. https://doi.org/10.1002/jsfa.2318
83. Venskutonis PR, Kraujalis P. Nutritional components of amaranth seeds and vegetables: a review on composition, properties, and uses. Compr Rev Food Sci Food Saf. 2013;12:381–412. https://doi.org/10.1111/1541-4337.12021
84. Tang Y, Tsao R. Phytochemicals in quinoa and amaranth grains and their antioxidant, anti-inflammatory, and potential health beneficial effects: a review. Mol Nutr Food Res. 2017;61:1600767. https://doi.org/10.1002/mnfr.201600767
85. Tang Y, Li X, Chen PX, Zhang B, et al. Assessing the fatty acid, carotenoid, and tocopherol compositions of amaranth and quinoa seeds-grown in Ontario and their overall contribution to nutritional quality. J Agric Food Chem. 2016;64(5):1103–10. https://doi.org/10.1021/acs.jafc.5b05414
86. Ayorinde FO, Ologunde MO, Nana EY, Bernard BN, Afolabi OA, Oke OL, et al. Determination of fatty acid composition of amaranthus species. Am Oil Chem Soc. 1989;66(12):1812–4. https://doi.org/10.1007/BF02660754
87. Palombini SV, Claus T, Maruyama SA, Gohara AK, Souza AP, et al. Evaluation of nutritional compounds in new amaranth and quinoa cultivars. Food Sci Technol. 2013;33:339–44. https://doi.org/10.1590/S0101-20612013005000051
88. Cabral CE, Klein MRST. Phytosterols in the treatment of hypercholesterolemia and prevention of cardiovascular diseases. Arq Bras Cardiol. 2017; 109(5):475–82. https://doi.org/10.5935/abc.20170158

89. Silverman MG, Ference BA, Im K, Wiviott SD, Giugliano RP, Grundy SM, et al. Association between lowering LDL-C and cardiovascular risk reduction among different therapeutic interventions: a systematic review and metaanalysis. JAMA. 2016;316(12):1289–97. https://doi.org/10.1001/jama.2016.13985
90. Marcone MF, Kakuda Y, Yada RY. Amaranth as a rich dietary source of beta-sitosterol and other phytosterols. Plant Foods Hum Nutr. 2003; 58:207–11. https://doi.org/10.1023/B:QUAL.0000040334.99070.3 e
91. Berger A, Monnard I, Dionisi F, Gumy D, Hayes KC, Lambelet P. Cholesterol-lowering properties of amaranth flakes, crude and refined oils in hamsters. Food Chem. 2003;81:119–24. https://doi.org/10.1016/S0308-8146(02)00387-4
92. Ogrodowska D, Zadernowski R, Czaplicki S, Derewiaka D, Wronowska B. Amaranth seeds and products – the source of bioactive compounds. Polish J Food Nutr Sci. 2014;64:165–70. https://doi.org/10.2478/v10222-012-0095-z
93. LehmannJ W, Putnam DH, Qureshi AA. Vitamin-e isomers in grain amaranths (*Amaranthus* spp.). Lipids. 1994;29:177–81. https://doi.org/10.1007/BF02536726
94. Barba de la Rosa AP, Inge S, Fomsgaard IS, Laursen B, et al. Amaranth (*Amaranthus hypochondriacus*) as an alternative crop for sustainable food production: phenolic acids and flavonoids with potential impact on its nutraceutical quality. J Cereal Sci. 2009;49:117–21. https://doi.org/10.1016/j.jcs.2008.07.012
95. Soriano-García M, Arias-Olguín II, Montes JPC, Rosas-Ramirez DG, et al. Nutritional functional value and therapeutic utilization of Amaranth. J Anal Pharm Res. 2018;7:596–600. https://doi.org/10.15406/japlr.2018.07.00288
96. Paśko P, Sajewicz M, Gorinstein S, Zachwieja Z. Analysis of selected phenolic acids and flavonoids in *Amaranthus cruentus* and *Chenopodium quinoa* seeds and sprouts by HPLC. Acta Chromatogr. 2008;20: 661–72. https://doi.org/10.1556/achrom.20.2008.4.11
97. Esatbeyoglu T, Wagner AE, Schini-Kerth VB, Rimbach G. Betanin--a food colorant with biological activity. Mol Nutr Food Res. 2015; 59(1):36–47. https://doi.org/10.1002/mnfr.201400484
98. Cahill J. Ethnobotany of chia, *Salvia hispanica* L. (Lamiaceae). Econ Bot. 2003;57:604–18. https://doi.org/10.1663/0013-0001(2003)057[0604:EOCSHL]2.0.CO;2
99. Pelaez P, Orona-Tamayo D, Montes-Hernandez S, Valverde ME, et al. Comparative transcriptome analysis of cultivated and wild seeds of *Salvia hispanica* (chia). Sci Rep. 2019;9:9761. https://doi.org/10.1038/s41598-019-45895-5
100. Beltrán-Orozco MC, Romero MR. La Chía, Alimento Milenario; Departamento de Graduados e Investigación en Alimentos. I. P. N Mexico: E. N. C. B; 2003.
101. Muñoz LA, Cobos A, Diaz O, Aguilera JM. Chia seed (*Salvia hispanica*): an ancient grain and a new functional food. Food Rev Int. 2013;29: 394–408. https://doi.org/10.1080/87559129.2013.818014
102. Ayerza R, Coates W. Protein content, oil content and fatty acid profiles as potential criteria to determine the origin of commercially grown chia (*Salvia hispanica* L.). Ind Crop Prod. 2011;34:1366–71. https://doi.org/10.1016/j.indcrop.2010.12.007
103. Grancieri M, Duarte Martino HS, Gonzalez de Mejia E. Chia seed (*Salvia hispanica* L.) as a source of proteins and bioactive peptides with health benefits: a review. Compr Rev Food Sci Food Saf. 2019; 18:480–99. https://doi.org/10.1111/1541-4337.12423
104. Mihafu FD, Kiage BN, Okoth JK, Nyerere AK. Nutritional composition and qualitative phytochemical analysis of Chia seeds (*Salvia hispanica* L.) grown in East Africa. Curr Nutr Food Sci. 2020;16:988–95. https://doi.org/10.2174/1573401315666191125105433
105. Nitrayova S, Brestensky HJ, Patras P, et al. Amino acids and fatty acids profile of chia (*Salvia hispanica* L.) and flax (*Linum usitatissimum* L.) seed. Potravinarstvo. 2014;8:72–6. https://doi.org/10.5219/332
106. Valevskaya L, Iegorova A, Ovsiannykova L, Sokolovskaya O, Marchenkov F, Shulyanska A. Nutritional properties of chia seeds and their sanitary safety. Food Sci Technol. 2020;14(2):96–102. https://doi.org/10.15673/fst.v14i2.1716
107. Reyes-Caudillo E, Tecante A, Valdivia-Lopez MA. Dietary fibre content and antioxidant activity of phenolic compounds present in Mexican chia (*Salvia hispanica* L.) seeds. Food Chem. 2008;107:656–63. https://doi.org/10.1016/j.foodchem.2007.08.062
108. Ullah R, Nadeem M, Khalique A, Imran M, Mehmood S, Javid A, et al. Nutritional and therapeutic perspectives of Chia (*Salvia hispanica* L.): a review. J Food Sci Technol. 2016;53(4):1750–8. https://doi.org/10.1007/s13197-015-1967-0
109. Martínez ML, Marín MA, Salgado Faller CM, Revol J, Penci MC, Ribotta PD. Chia (*Salvia hispanica* L.) oil extraction: study of processing parameters. J Food Sci Technol. 2012;47:78–82. https://doi.org/10.1016/j.lwt.2011.12.032
110. Ciftci ON, Przybylski R, Rudzinska M. Lipid components of flax, perilla, and chia seeds. Eur J Lipid Sci Technol. 2012;114:794–800. https://doi.org/10.1002/ejlt.201100207
111. Rokosik E, Dwiecki K, Siger A. Nutritional quality and phytochemical contents of cold pressed oil obtained from chia, milk thistle, nigella, and white and black poppy seeds. Grasas Aceites. 2020;71(3):e368. https://doi.org/10.3989/gya.0679191
112. da Silva BP, Anunciação PC, da Silva-Matyelka JC, Della Lucia CM, et al. Chemical composition of Brazilian chia seeds grown in different places. Food Chem. 2017;221:1709–16. https://doi.org/10.1016/j.foodchem.2016.10.115
113. Hrncic MK, Ivanovski M, Cör D, Knez Z. Chia seeds (*salvia Hispanica* L.): an overview—phytochemical profile, isolation methods, and application. Molecules. 2020;25(1):11. https://doi.org/10.3390/molecules25010011
114. Demir EA, Bilgic Y. Chia seed (*Salvia hispanica* L.) supplementation may contribute to raising the levels of vitamin B12: an option for the vegan diet. Revista de Nutrição/Brazilian. J Nutr. 2019;32:e180249. https://doi.org/10.1590/1678-9865201932e180249
115. Nogalska A, Momot M, Sobczuk-Szul M, Pogorzelska-Przybyłek P, Nogalski Z. Calcium and magnesium contents in the milk of high-yielding cows. J Elem. 2017;22:809–15. https://doi.org/10.5601/jelem.2016.21.4.1365
116. Pigni NB, Aranibar C, Mas AL, Aguirre A, et al. Chemical profile and bioaccessibility of polyphenols from wheat pasta supplemented with partially-deoiled chia flour. LWT- Food Sci Technol. 2020;124: 109134. https://doi.org/10.1016/j.lwt.2020.109134
117. Oliveira-Alves SC, Vendramini-Costa DB, Cazarin CBB, Júnior MRM, et al. Characterization of phenolic compounds in chia (*Salvia hispanica* L.) seeds, fiber flour and oil. Food Chem. 2017;232:295–305. https://doi.org/10.1016/j.foodchem.2017.04.002
118. Martínez-Cruz O, Paredes-López O. Phytochemical profile and nutraceutical potential of chia seeds (*Salvia hispanica* L.) by ultrahigh performance liquid chromatography. J Chromatogr. 2014;1346:43–8. https://doi.org/10.1016/j.chroma.2014.04.007

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