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Chapter 3

The Revival of Quinoa: A Crop for Health

Mariane Lutz and Luisa Bascuñán-Godoy

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Abstract

Quinoa (*Chenopodium quinoa* Willd.) is a basic food in pre-hispanic Andean communities, used not only as a food but also for medicinal purposes. The interest in quinoa has increased because of its plasticity to adapt to environmental conditions: it tolerates frost, salinity and drought; it grows on marginal and arid soils and high altitudes. The nutritional quality of quinoa is well recognized: protein content ranges 13–17 g/100 g, with an amino acid score above 1.0 and it is gluten free. The grain contains starch and free sugars, with a glycemic index ranging 35–53, depending on the cooking time. It also contains bioactive phytochemicals such as dietary fiber, carotenoids, phytosterols, squalene, fagopyritols, ecdysteroids and polyphenols. The composition of quinoa varies among ecotypes and is affected by environmental factors: some amino acids and phytochemicals augment under stress episodes. The rationale for the revival of quinoa and its reintroduction into the diet is related with the epidemiological situation, which includes diseases that exhibit risk factors that may be reduced with a balanced nutritious diet, in which quinoa plays a major role, being considered as a "superfood." Moreover, it is one of the crops selected by Food and Agriculture Organization (FAO) to offer food security.

Keywords: quinoa, *Chenopodium quinoa* Willd., ancient crop, nutritional quality, chemical composition, bioactives, health, crop plasticity

1. Introduction

Since 1998, the WHO has considered obesity as an epidemic affecting the globe, a condition related to more deaths than undernutrition in the whole planet. Obesity is associated with various noncommunicable diseases (NCD) such as cardiovascular diseases, cancer and diabetes, among others. Globally, two out of three deaths each year are attributable to NCD. In this context, it is very important to take into account some alimentary traditions and the social value of food practices that have been lost with time. Most of the traditional culinary practices, beliefs, attitudes and meanings of certain foods have been neglected and traditional crops have been left aside, missing the food cultural practices of different regions.

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An outstanding food crop that has been almost lost is quinoa (*Chenopodium quinoa* Willdenow), a South American dicotyledonous primary crop (an indehiscent achene: a seed-like fruit with a hard coat) that has become an extremely popular food product in the last decades. The seeds (approximately 2.5 mm in length and 1.0 mm in diameter) are flat white, yellow, red, brown and black, whereas the seed coats have a brown color and possess excellent nutritional properties (**Figures 1** and **2**).

1.1. Quinoa plant: origin and botanical properties

Chenopodium quinoa Willd. is an annual gynomonoecious plant with an erect stem, alternate leaves and flowers clustered together to form the inflorescence in a panicle that measures from 15 to 70 cm long [1]. The basic chromosome number of quinoa is $x = 9$ and their somatic chromosome number is $2n = 4x = 36$, suggesting that it is an allotetraploid plant [2]. Measurements of chromosome arm length ratios in quinoa indicate an allopolyploid, which is consistent with it high degree of self-fertility and low levels of inbreeding depression seen in this species [3].



Figure 1. Chilean quinoa plants.

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Figure 2. Collected seeds of quinoa.

Quinoa was one of the basic foods in pre-Hispanic communities of the Andean Region, grown for over 7000 years mainly in the current locations of Peru, Bolivia, Ecuador, Chile, Argentina and Colombia, from 2° North latitude (Colombia) to 47° South latitude (Chile) [4–6]. The name refers to "the mother grain" by the Andean people and it was used not only as a food but also for medicinal purposes. The colonists suppressed its cultivation and the remaining crops that survived were cultivated practically hidden in small areas [7]. The locals have preserved quinoa in its natural state, including its many varieties, as food for present and future generations.

Quinoa represents a cultural heritage in many Latin-American countries. It has survived from extinction in different agroecological zones, ranging from the extremely dry Altiplano highlands at 4000 m above sea level with average rainfall of 150 mm per year to coastal zones of central and southern Chile, where soils are clayish and rainfall is above 1000 mm/year [8]. It spread throughout the central and north-central Andean valleys and southwards into the Araucanian coastal region and adjacent Patagonia, diversifying into its five principal ecotypes. The crop is produced mainly in Bolivia, Peru and Ecuador, with efforts to cultivate it worldwide and the diversity has been described by five major ecotypes linked to the geographical region: Altiplano (Peru and Bolivia), Inter-Andean valleys (Bolivia, Colombia, Ecuador and Peru), Salt lands (Bolivia, Chile and Argentina), Yunga (Peru, Bolivia and Argentina) and Coastal (Chile) [9, 10].

Miranda et al. [11] observed genetic differentiation among the geographic distribution of quinoa genotypes, which were expressed in morphological, yield responses, chemical composition and functional properties in a common garden assay of six selected genotypes. Using this model, the high capacity of adaptation of the seeds to different environments has been demonstrated [12]. Moreover, these properties of quinoa seeds allow this crop to be used under environmental extreme conditions in countries facing challenges such as drought and salinity under very diverse agroclimatic conditions globally [1].

There are currently more than 6000 varieties of quinoa cultivated by farmers [13]. Due to the wide range of genotypes (including 250 varieties), the possibilities of adaptation to many abiotic stresses abroad have increased significantly the interest of quinoa cultivation [14]. The plant exhibits an enormous adaptability to different environments, including the harsh conditions that characterize much of the Andean zone. Therefore, the production has spread through many different countries, including Japan, Australia, Spain, Germany, England, Sweden, Denmark, the Netherlands, Italy, France, Finland, Kenya, Ethiopia, India, the USA, Canada, among others. Many reports indicate that quinoa is an interesting alternative crop for the use of deteriorated and poor soils [5] and it has been successfully tested in various countries in Asia, the Near East and North Africa [6]. In fact, the enormous plasticity of quinoa includes tolerance to frost, salinity and drought, it has the ability to grow on marginal and arid soils and is also adapted to high altitudes [15–18]. The strong tolerance to drought and salinity allows it to resist the current and future challenges of the global climate change, including water shortage [15]. The plant adapts well to climates ranging from desert dry weather to relative humidity from 40 to 88%, with temperatures from −4°C to 38°C.

Several genotypes of quinoa are able to maintain a high photosynthetic efficiency under water-deficit conditions [19, 20] and to quickly reestablish photosynthesis after a period of rehydration [21–24]. Quinoa shows an extraordinary physiology of adaptation to stress, particularly its highly efficient use of water [8], that is, the quantity of grain obtained per liter of water used is another useful criterion for comparing quinoa with cereals. Martinez [25] reported 500 L water per kilogram quinoa, a significantly lower water-use footprint compared with rice (2497 L/kg) or maize (1222 L/kg), figures that are even greater if one considers also quantity of protein per kilogram. Crop production is acceptable with rain amounts of 100–200 mm [26]. The drought tolerance of quinoa has been attributed to a reduction in leaf area [23, 24, 27], the presence of calcium oxalate vesicles in leaves, which could reduce the transpiration rate [22, 28] and their branched and dense root system, which is able to penetrate into 1.5 m sandy soil [22, 27].

Regarding the metabolism of quinoa during periods of drought stress, it has been suggested that the induction of antioxidant molecules related with nitrogen metabolism is very important [29]. In fact, drought increases the amount of glutamine in quinoa leaves, which is the main form in which nitrogen is translocated to the grains [30]. Therefore, drought stress episodes increase the content of various amino acids, including Phe, Val, Trp and Met. These changes in quality could compensate the decline of the seed yield under stressful conditions. It has been suggested that the ornithine cycle and induction of amino acids could play a key role in the response to water scarcity and subsequent restoration under conditions of rehydration [29, 30]. Moreover, the aromatic amino acids Phe, Tyr and Trp are the main precursors of bioactive

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secondary metabolites, including the biosynthesis of flavonoids and alkaloids [31], most of which exhibit healthy properties [32]. The physiological relationship between the induction of amino acid synthesis and the production of healthy secondary metabolites is under investigation.

2. Quinoa: a traditional crop and a "superfood"

2.1. Nutrients in quinoa

The proximate analysis of quinoa seeds is shown in **Table 1**.

Quinoa proteins are recognized for their high amount [18, 33–40] and good quality, which was reported for the first time by White et al. in the 1950s [41], who described that the quality of quinoa protein was equal to that of whole dried milk protein when fed to rats. Later, it was reported that pigs fed cooked quinoa grew as well as those fed dried skimmed milk [42]. Proteins exhibit a high content of Lys (4.8 g/100 g) and Thr (3.7 g/100 g), which are in general the limiting amino acids in conventional cereals [43], along with a good albumin/globulin balance and an amino acid score above 1.0 [38, 44–46]. The excellent quality of protein is maintained even taking into account that the amino acid profile is affected by environmental factors [47].

	References							
Component	**[18]**	**[34]**	**[36]**	**[37]^{a}**	**[37]^{b}**	**[38]**	**[39]**	**[40]**
Protein	16.8	12.9	13.1	14.7	12.8	14.1	16.5	12.6
Carbohydrates	51.4	63.7	59.9	59.1	68.4	57.2	69.0	67.3
Lipids	5.9	6.5	5.7	6.4	6.2	6.1	6.4	5.7
Fiber	12.1	13.9	11.7	1.9*	1.5*	7.0	1.9*	3.0*

*Expressed as Crude Fiber.
[37] ^{a} var. Regalona.
[37] ^{b} var. Ancovinto.

Table 1. Proximate analysis of quinoa seeds (mean values, g/100 g DW).

Several methods to obtain protein isolates have been described [35, 48], consisting mainly of 11S globulins and 2S albumins, the main contributor of sulfur amino acids Cys and Met, which are limiting in legumes and they also contain interesting amounts of Arg [49]. Also, various high protein-rich fractions of interest can be obtained for the food industry [50]. An additional nutritional advantage of quinoa is that it may be consumed by celiac patients, since it is considered a gluten-free grain because it contains low concentrations of prolamins [51] and has a distant phylogenetic link with gluten containing cereals such as gramineas (wheat, barley and rye). In spite of this, the ability of quinoa cultivars to stimulate gliadin-specific T cell lines and other immune responses is still under investigation [52].

Quinoa seeds have moderate lipid content (5–9 g/100 g), with an interesting fatty acids profile. Compared with rice oil, quinoa oil contains over 20 times more unsaturated fatty acids. The main saturated fatty acid is palmitic (16:0, around 10%), whereas the main unsaturated fatty

acids are oleic (18:1n-9; 20-30%), linoleic (18:2n-6; 49–57%) and α-linolenic (18:3n-3; 8.5–12%), corresponding to 87–88% of the total [34, 37]. The oil also contains various tocopherols [39, 46] and other minor lipid constituents.

Among carbohydrates (51–70 g/100 g), the grain contains starch and free sugars (glucose, fructose, sucrose and maltose). Another healthy property of quinoa grains is their glycemic index (GI), which represents a ranking of carbohydrates on a scale from 0 to 100 according to their impact on blood sugar levels during the 2 h following consumption. For quinoa, the GI ranges 35–53, depending on the cooking time, which are considered low values on the glucose reference scale [53], whereas rice GI values range from 75 to 89 [14]. This property is related with the dietary fiber content of quinoa (7–14 g/100 g), since the fiber contained in the grain affects the digestibility of nutrients, including carbohydrates and the absorption of glucose occurs at a lower rate through a longer area in the gut, lowering the postprandial peak of blood insulin. Most fiber is insoluble, containing galacturonic acid, arabinose, galactose, xylose and glucose, whereas the soluble fiber is composed mainly of glucose, galacturonic acid and arabinose and arabinose-rich pectic polysaccharides [54]. Additionally, the intake of quinoa has been associated with satiety and appetite control in animal models [55] and humans [56], although further studies are required on this subject.

The grain is also a good source of minerals, exhibiting high amounts of potassium, calcium, magnesium, copper, iron, manganese and zinc [57–59], which are higher than those of conventional cereals [60] and the calcium-phosphorus ratio (1:0.7–3.9) is better than that of cereals (1:7.8–54.0) [34]. Among vitamins, the B complex is outstanding [61], with a high level of folate [38].

2.2. Bioactives in quinoa

Quinoa is often considered a natural functional food, a property that represents a benefit for health that is generally associated with the presence of bioactive phytochemicals. The crop is recognized as a good source of multiple bioactives, including dietary fiber, carotenoids, phytosterols, squalene, fagopyritols, phytoecdysteroids and phenolic compounds [40, 61–66].

Among phenolics, the seeds contain flavonoids such as quercetin and kaempferol glycosides, ferulic acid, phytic acid (the main storage form of P in the plant) and tannins [67–69]. Most of the phenolics in quinoa exhibit antioxidant activity [70–72] and the total antioxidant capacity is further increased by non-phenolic compounds [73]. The interest on phenolics is not only due to their antioxidant properties but also since they present antiallergic, anti-inflammatory, anticarcinogenic, cardiovascular protective properties, among other beneficial effects for health [74, 75]. In a comparative study, Gorinstein et al. [76] showed that pseudocereals have higher antioxidant activity than some cereals (e.g. rice and buckwheat), whereas Laus et al. [77] reported that antioxidants from quinoa seeds may be more readily accessible than those in wheat species. Hirose et al. [78] observed that the amounts of phenolics such as quercetin and kaempferol in quinoa grown in Japan are higher than those of conventionally used edible plants. On the other hand, when cooking or dehydrating quinoa an increase in temperature leads to a reduction in the total phenolics content [79].

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Quinoa leaves also contain a high level of phenolics [80], which exhibit anticarcinogenic effects in vitro, linked with inhibitory effects on the proliferation, motility and cellular competence of cancer cells [81]. However, the effects depend on the technological processes and the food matrix in which quinoa grains or leaves are included. For instance, Swieka et al. [82] formulated supplemented bread with phenol-rich quinoa leaves and observed an improvement of the antioxidant activity of the product obtained, although not as high as expected, probably due to the blocking of reactive groups of phenolic compounds by bread components. Some phenolic compounds in quinoa also inhibit α-amylase and α-glucosidase activities, enzymes involved in the breakdown of starch and derivatives, which allows for better control of intestinal glucose absorption and therefore of postprandial glycemia [68, 83]. Moreover, quinoa seeds are also a source of a different kind of phenolics: isoflavones, among which the main are genistein and daidzein [66]. These molecules are usually named as "phytoestrogens," due to their structural similarity with β-estradiol (an estrogen) and exhibit a wide range of beneficial effects [84].

Among the secondary metabolites, betalains are quantitatively important in several genotypes of quinoa. In fact, quinoa belongs to one of the 13 families of betalain producers [32]. These chromoalkaloids are water-soluble pigments containing nitrogen and include the red-violet betacyanins and the yellow betaxanthins. Studies performed with several genotypes of quinoa indicate that contrastingly with the *Amaranthus* genus, where the principal betalains are amaranthine and isoamaranthine, in quinoa, the main compounds are betanin and isobetanin [85]. Recently, it has been proposed that betanin is a good scavenger of reactive oxygen species and prevents low-density lipoprotein (LDL) oxidation and DNA damage [86].

Another type of secondary metabolites in quinoa is phytoecdysteroids (polyhydroxylated steroids), structurally related to insect molting hormones, that have been implicated in plant defense since they protect them against nonadapted insects and nematodes [87]. The seeds contain ecdysteroids in amounts ranging from 450 to 1300 μg/g [88]. The main form is 20-hydroxyecdysone (30 μg/g) and several minors have been reported in a range of 3–9 μg/g, including makisterone A, 24-epi-makisterone A, 24,28-dehydro-makisterone A and 20,26-dihydroxyecdysone [89]. Dini et al. [43] showed that quinoa flour contains both 20-hydroxyecdysone and kancollosterone and Nsimba et al. [73] described the presence of a new set of ecdysteroids. The ecdysteroid content of quinoa seeds from different sources shows significant variations. These molecules are rather stable during food processing, representing an intake of 20-hydroxyecdysone that may have positive effects on human health (**Figure 3**) [65].

A characteristic feature of quinoa grains is the presence of saponins (triterpenoid glycosides) in the outer layer. These secondary metabolites are utilized by the plant as a predator repellent and exhibit a series of pharmacological properties [90, 91] and impart a bitter taste. Consequently, saponins are reduced for debittering by various methods that remove the hulls (abrasive processes, washing). The amount in the grains depends on the cultivar and can be classified into "sweet" (<0.11%) or "bitter" (>0.11%) [92].

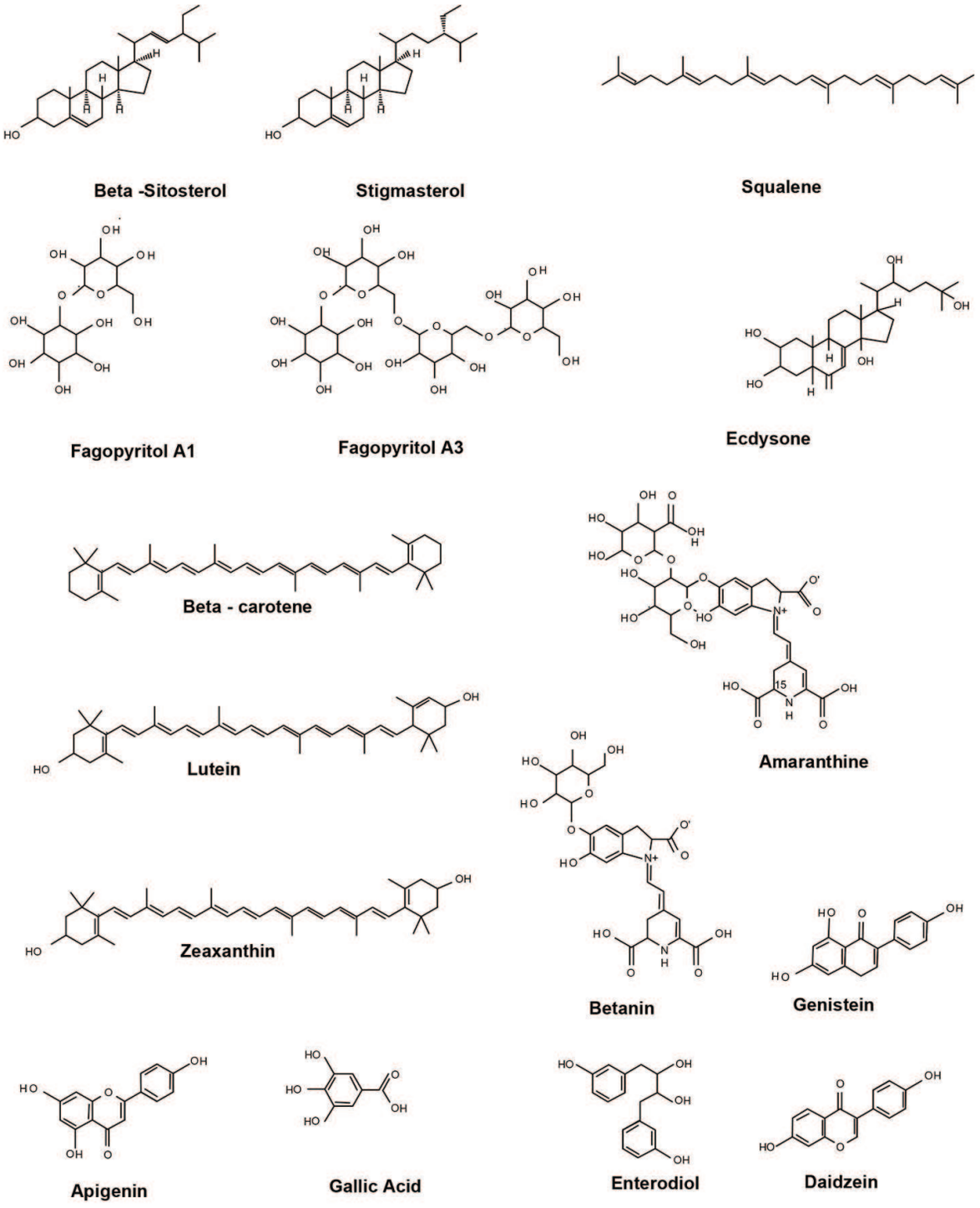


Figure 3. Bioactive molecules in quinoa.

Although all the grains exhibit excellent nutritional properties, it is necessary to take into consideration that the chemical composition of quinoa varies among ecotypes, that is, according to groups of cultivars and/or landraces defined according to distributional, ecological, agronomic and morphological criteria due to strong genetic variability in addition to environmental differences in the Andean region [93]. Moreover, the nutritional composition

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varies in relation with the environmental stress factors and several research groups have described changes in nutritional aspects of seeds as a result of environmental stress episodes. For instance, Panuccio et al. [94] reported that under high salt conditions, phenolic content and antioxidant capacity of quinoa seeds increased. Miranda et al. [11] compared two Chilean genotypes grown under arid and cold-humid environments, showing that in cold rainy zones the size and weight of the seeds increased, whereas under hot arid conditions, phenolic compounds and components of proximate analysis (except proteins) increased.

The quality and amount of protein in the seed has also led to the search of bioactive peptides, among which antihypertensive angiotensin I converting enzyme (ACE) inhibitory peptides has been demonstrated [95–97]. On the other hand, protein ingredients not only provide nutrition but also good technological properties to facilitate food processing. The technological functional properties of quinoa proteins are well recognized, since they provide emulsifying capacity and emulsion stability, which affect foods by acting on the membrane matrix that surrounds the oil drop in an emulsion, preventing its coalescence [98]. Moreover, quinoa proteins show a high foaming capacity and stability [99].

The nutritional properties of quinoa and specifically the high quantity and quality of protein, allow the use of protein isolates in the formulation of various foods. A series of patents have been described in relation with their production, processing and uses. Just to mention a couple of examples, patent US 7563473 B2 relates to "quinoa protein concentrate" (QPC), which contains at least about 50 wt% protein which is food grade and/or pharmaceutical grade and methods of preparing such protein concentrates as well as starch, oil and fiber from quinoa grain, whereas patent US 20100196569 A1 involves grain products having a reduced bitter flavor with a sweet taste or crunchy texture, among many others. Another line of work is related with the multiple industrial uses of the saponins obtained from quinoa grains, including their processing, for example, in the pharmaceutical industry as immunological adjuvants, to stimulate nonspecific immunity, as well as to enhance an immunological response to a selected antigen and to enhance mucosal absorption of some drugs. As such given examples, many other uses of quinoa seeds and coproducts have been described.

The grain shows a high versatility for culinary uses, but other parts may also be used in cooking: the parts of the plant that have been used as food ingredients include the seed, leaves, stems and roots. The mostly used form of quinoa is the cooked grain (soups, stews), followed by various other forms such as toasted seeds, tender leaves (soups, crepes, pancakes, tortillas), flour (bakery products such as breads, biscuits, cookies, muffins), as well as nutrition bars, granolas, confections and various beverages, fermented or not. Quinoa grains and by-products (e.g. hay) are also used for animal feed.

The nutritional quality of quinoa grains is well recognized, even by agencies such as the National Research Council and the National Aeronautics and Space Administration (NASA) [100], which included quinoa as part of the controlled ecological life support system (CELSS). As described, this ancient crop is nutritious and healthy, with high adaptability that can withstand food processing and can also be used as a replacement for allergenic nuts and seeds. It can support sustainable production and FAO selected it as one of the crops destined to offer food security, by promoting quinoa as part of a FAO strategy to encourage the cultivation of traditional crops [101].

3. Conclusion

The rationale for the reintroduction of quinoa into the diet is strongly related with the epidemiological situation prevailing, which is similar in many nations around the world: growing rates of child obesity, high prevalence of obesity during/after pregnancy in women, high rates of NCD such as cardiovascular, diabetes, cancer, which are associated with the major causes of death. From the nutritional point of view, quinoa represents an excellent source of nutrients and bioactive phytochemicals that contribute to a healthy diet and, on the other hand, supplies good quality protein to support children's healthy growth. The chemical composition of different cultivars is outstanding, although it may be affected by the environmental and climatic factors. Taking into account all its properties, quinoa is currently promoted as an extremely healthy food ("superfood"), the so-called food of the twenty-first century.

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