11 Quinoa—Evolution and Future Perspectives

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Abstract

Quinoa (*Chenopodium quinoa*, Willd.) is a high-quality protein grain originating in the Andean region. Once a staple of the Incas, from being unknown in the rest of the world, this grain has recently become a global commodity. This is largely due to its nutritional qualities and adaptation to a wide range of environments. While the majority of quinoa is produced in South America, especially in Peru, Bolivia and Ecuador, production is increasingly spreading across the globe. The production in the area of origin of this grain is becoming increasingly intensive and replacing traditional smallholder production. The International Year of Quinoa catalysed the growth of quinoa in 2013 and led to an increased demand, production and research of quinoa worldwide. Nutrition qualities that made quinoa popular are the high-quality protein, a range of functionalities related to the nutrients contained in this grain, besides being a gluten free food. Quinoa is well adapted to different latitudes and production under marginal conditions such as drought or salinity. These qualities are used by breeders to develop high yielding cultivars for their regions. New food products containing quinoa are in continuous development. Additionally, this high-quality protein grain with low glycemic index is promoted as a healthy food for celiac and diabetic patients and in the recent vegan, vegetarian or flexitarian diets. Future perspectives for quinoa point to the expected increase of its production around the world. Environmentally, this can bring positive benefits. It represents a nutritious crop for areas affected by climate change. Quinoa also constitutes an alternative to meat that reduces greenhouse gas emissions, furthermore, using this grain increases the use of biodiversity. There are a number of challenges to be addressed, in particular with regards to research into abiotic and biotic stresses, development of new cultivars, saponin reduction and ensuring recognition and fair sharing of genetic materials.

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11.1 Introduction

Quinoa (*Chenopodium quinoa*, Willd.) is a grain originating in the Andean region that has recently being spread globally due to the increasing attention to its nutritional qualities and adaptation to a wide range of environments. These characteristics have attracted the interest of scientists who started to study and develop the production systems to grow this crop in other areas of the world, and at the same time, market demand has increased globally. The following chapter briefly synthesises quinoa development as a crop, in science and in the food markets. It includes some examples from the region of origin and the new areas of production to show different perspectives for this crop. With an overview and analysis of the past and the current challenges, it is possible to draw quinoa´s future perspectives.

11.2 Evolution and Perspectives of Quinoa as a Crop

11.2.1 Production Areas

Quinoa originated in the southern Andes and domestication began before 3000 BC, independently in the highlands and coastal regions as suggested by relevant studies (Bruno 2006; Jarvis et al. 2017). Quinoa was an important part of the Andean diet, at the arrival of the Spanish in the XV century the crop reduced in importance due to the cultivation of the new species brought from the old world (Gandarillas 1979). However, it has experienced a revival in the last century. According to the latest statistical available data from 2018, Bolivia, Peru and Ecuador are now the major quinoa producers, covering 172,000 ha with this grain and producing around 70–80% of global quinoa volumes (Alandia et al. 2020).

In the 1930s, quinoa experiments began in Kenya, and then in the 1970s and 1980s in North America and Europe, moved by the demand for healthy foods and interest in new crops for diversification (Galwey 1993). By the end of the 1980s quinoa was either under research or produced in 11 countries outside the Andes. By the year 2000, the USA and Canada were producing 10% of global quinoa (Alandia et al. 2011). After the International Year of Quinoa (IYQ) in 2013, 75 countries were testing quinoa, with 26 registered cultivars in existence. Quinoa now is in research or production in 123 countries (Fig. 11.1). By 2018, the United States, Canada, the Netherlands and Spain participated in the 15–20% of global exports in the world. The remaining is still produced by Peru and Bolivia (ITC 2019; Alandia et al. 2020).

11.2.2 Production Systems

In the Andean highlands, quinoa is generally produced on small-medium farms, under traditional production systems dependent on rain and using low input technology (Alandia et al. 2020). On small-scale farming, sowing, management and harvesting are manual or semi-mechanised. Production can be highly impacted by extreme weather events, such as El Niño and la Niña, which can drastically damage seed yields. Crops are often affected by water shortages, poor soils, salinity and frost up to 200 nights of the year (Jacobsen 2003). There is also extensive quinoa production for export, in the southern highlands of Bolivia, which continues to be produced under traditional and extreme environmental conditions, while in the Peruvian coastal region quinoa for export is produced more intensively. In the Andean region, quinoa yields remained below 1 t/ha until 2014. After, they surpassed 1 t/ha with 1.6 t/ha from Peru, 1.2 t/ha from Ecuador, while it remained at only 0.52 t/ha in Bolivia. Around 30–40% of quinoa produced in Peru, Bolivia and Ecuador is organic. The majority of organic quinoa is exported from Bolivia, while Peru exports most conventionally produced quinoa (IBCE 2015; Oficina Internacional del Trabajo 2015; Alandia et al. 2020).

Outside of the Andean region, production is increasing. In North America, the main area of quinoa cultivation is in the prairie areas of Canada, since the 1990s, and in the state of Colorado in the US. It is likely to have most success in high altitude areas in the American Rockies and the Canadian Prairies, as well as in high altitude areas. It also

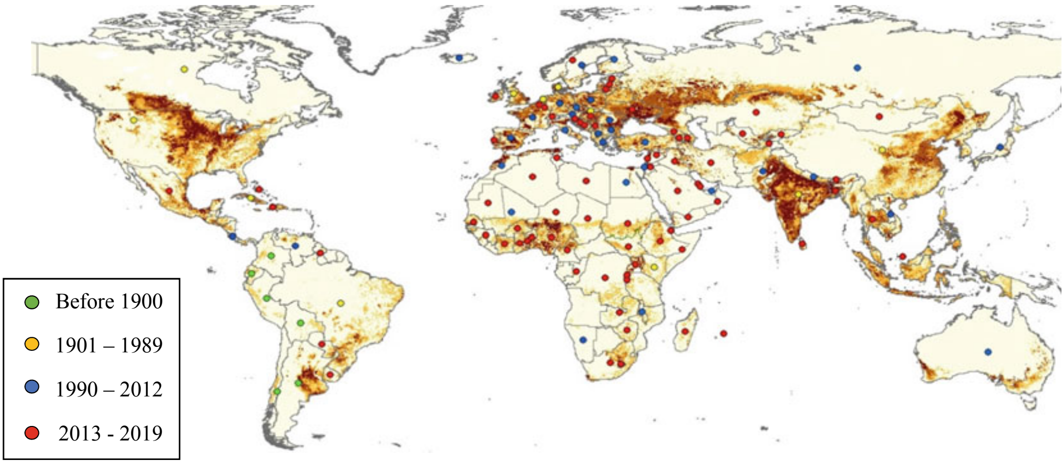


Fig. 11.1 Quinoa presence in the World (adapted with data from Alandia et al. 2020)

showed potential for winter cropping in California (Peterson and Murphy 2013).

In Europe, commercial production of quinoa already exists in Spain, France, the Netherlands, Italy, Denmark to mention some, and this grain is in research in many other countries as it is shown in Fig. 11.1. In many of these countries, production has rapidly increased in the last few years under technified production systems of organic and conventional agriculture. Across Europe, the area under cultivation increased from 0 to 5000 ha and by 2018, countries such as France and Spain were already considered medium producers with areas between 500–5000 ha (Alandia et al. 2020). For example In Denmark, quinoa production area has increased from 6 ha in 2015 to 159 ha in 2018, 26 times more in only three years (Landbrygsstyrelsen 2018).

In 2016, new production was mainly limited to small areas of intensive and experimental agriculture, with predominant mechanised systems. New trials were reported in 95 countries; many of these being countries such as Algeria, Iraq, Mauritania, Yemen, Ethiopia, Senegal, Kyrgyzstan, Sri Lanka and Bhutan, to mention some (Bazile et al. 2016a).

11.2.3 Perspectives

Global quinoa production is expected to increase in the future. This ancient grain started to be produced outside its region of origin in the early 1980s and from being produced mainly in six countries, it is now present across 123 countries of the world. The dispersal of quinoa has been fast compared with other species, mainly due to the high demand and rapid development of the market, its high level of adaptation and tolerance to abiotic stresses. This crop also has the quality to adapt to diverse farming systems as successful trials in different regions of the world have shown. From 2013 to 2018, quinoa was experimentally implemented in 72 countries. Half of the countries with the biggest surface cultivated with quinoa are now located outside the Andean region, i.e. Spain, France, China and Canada (Alandia et al. 2020). Perspectives are that production areas will increase in many of the countries where quinoa is now present only experimentally.

It is well known that meat production is one of the major factors negatively affecting the environment with GHG emissions, land, water and energy use (FAO 2006; Song et al. 2016; Godfray et al. 2018). Projections of global population growth estimate 9.6 billion people by 2050 and 10.6 by 2100 with higher concentrations in Africa and Asia (United Nations 2013). Meat demand was projected to increase by 76% by 2050 with a resulting increase of 80% of GHG (UNEP 2012). This increasing demand can be satisfied with alternative sources of protein to reduce damages to the environment. With the global agenda and international agreements beginning to address climate change, more countries have the obligation to come with efficient solutions. Developing alternative sources to meat is one of the answers through the production of plant protein food. Research is catalysing this process and more funding will become available for this target. With high nutritional qualities, quinoa is already one of the crop candidates chosen in existing projects addressing this objective to increase plant protein in Europe (e.g. PROTEIN2FOOD, Smart Protein). Moreover, quinoa is already well established in the global market and it diversifies global diets away from dependence on few commodities; just three crops make up over 50% of plant calories globally (Bioversity International 2017).

Due to its good adaptation to extreme environments, quinoa is a crop that enhances resilience of farming systems; its implementation in fragile areas might be targeted to increase production. In the future, conditions such as salinity and drought are likely to become problems that farmers have to address more frequently due to climate change. Tolerance to different abiotic stresses is therefore relevant for climate change scenarios, and crops such as quinoa, which produces well under marginal conditions, will be necessary to ensure food security.

Fig. 11.2 Genaro Aroni in light blue, addressing to quinoa producers in the Bolivian southern highlands during a field day (Photo credit: G. Alandia)

Genaro Aroni is a quinoa specialist from the southern highlands of Bolivia. He has 40 years' experience in agricultural production and has worked with quinoa for over 30 years. This interview took place in August 2019.

What changes have you seen in production in the time that you have worked with quinoa? I have seen dramatic changes. Between the 1940s–1960s, the area of the southern highlands was entirely addressed to cattle, and quinoa was produced only on the hillsides. Since the introduction of tractors in the 1970s, to plough the plains, quinoa production has become more widespread and intensive. Farmers moved from camelid livestock production to agriculture. By the 1990s, farmers wanted access to the market, and began to export both conventional and organic quinoa. With the boom of quinoa, production in Bolivia increased to over 90,000 t, mostly of organic. When prices increased, many members of the community returned to claim their land, which created problems. At the same time, there were serious debates about socio-economic problems, migration and population decline in many areas (Fig. 11.2).

Is quinoa production in the southern highlands still for export? Mainly organic quinoa is for export, while conventional quinoa is destined for internal consumption and export to Peru.

How do you evaluate quinoa yields in this region? Quinoa yields are low, and production does not correspond to agricultural areas. The extreme weather and environment of the southern highlands mean that yields have remained low, at around 0.5 t/ha until now. Some studies have shown that organic fertiliser can improve yields, but producers are not willing to pay for it. ***How are production costs***? In general, the cost of production is around €600–780/ha. The main cost is labour. During the quinoa boom, people were hired from outside the region, with salaries of €20/day, as well as accommodation and food, with up to eight or nine workers per plot. Since the price of quinoa fell, the salaries have fallen to €13–16/day, and you often see only one worker per plot.

How do the prices vary? In 2015, quinoa prices reached €5.70/kg, but by 2016 this had fallen to only €0.94/kg. The price of organic quinoa is now €2–2.20/kg, and €1.60/kg for conventional quinoa. Prices have improved slightly together with expectations.

What are the production problems/challenges? In the southern highlands, it is the loss of soil fertility aggravated by the recurring drought; 15 years ago, it rained from mid-December until the first days of March. Now the first rains occur on the first days of February, last only a month and are only half the quantity of water. Climate change is a problem and organic production under these conditions implies higher costs. Pests have increased, and now need treatment four times, when they only needed two treatments before.

What recommendations can you give for improvement? We have to include fallow systems again, add organic matter from camelid livestock, to reduce erosion and benefit reforestation processes, use barriers of native legume species where there has been deforestation and add grasses and biannual legumes that are tolerant to frost. We have tested Andean lupin, which can generate 14 t/ha of green manure. Other native species can produce 6 t of green manure per hectare, and there have been interesting results with fast-growing Andean grasses. We need much more research on wild legumes; we have more than 80 species that could be included. Another recommendation is to improve the sowing technology with the optimal sowing time. Finally, economic support is needed from the government to repopulate the area with llamas. With international production now, there will be competition in cost and quality, therefore Bolivia needs to remain competitive.

Do producers still consume quinoa? ***Do you***? At the national level, there is more consumption now than before, the latest data I have on annual consumption is around 2 kg/person. What I see in the southern highlands is that with the boom of quinoa, and the economic flow that occurred, people diversified their diets and began to access to other products. However, the price is still high, compared to rice and pasta. Yes, I do consume quinoa twice a month.

Anders Nørgaard is an agricultural technician at the University of Copenhagen's experimental farms in Denmark. He has worked with quinoa for over 25 years. This interview took place in August 2019. His answers are complemented with extra information from: Inger Bertelsen (IB), senior consultant in Ecology and Innovation at SEGES and Christian Høegh (CH) Business Developer for Food and Agriculture at Business Lolland-Falster.

How has quinoa production changed along the time you work with this crop? In Denmark, quinoa production started 10–12 years ago after many years of research. Production increase has been slow and concentrated in some islands. Quinoa production system is similar to spring barley. We sow these crops at around the same time, and harvest the quinoa around three weeks after barley. Quinoa used to be slow

Fig. 11.3 Anders Nørgaard after a harvest day at the research station of Copenhagen University (Photo credit: A. Odone)

maturing but now the varieties that we have mature early enough. We now harvest in early September, when we used to harvest in late September or October, which is too late for the Danish climate (Fig. 11.3).

Is production addressed for the local market? Yes, to my knowledge. (IB:) There are local companies buying quinoa produced in Denmark.

What are the yields of quinoa? Average yields here are around 1.2 t/ha. The highest yields were 2.9 t/ha, although sometimes yields can be very low.

How are production costs? (CH:) Production costs including cleaning would reach between €1,100–1,300/ha.

How do prices vary? (CH:) Farmers are hoping to get €3.3–3.4/kg for organic quinoa and €2.1–2.2/kg for conventional; however, not much is sold.

What are the main production problems? Farmers producing quinoa should be careful of three things: sowing depth, weeds and aphids. Harvesting is easy. We tried sowing quinoa at different row spacings, at 12 and 50 cm. This gave the same yields but at 50 cm it is much better for row cleaning.
Weeding is the main problem. The main weeds are 'hvidmelet gåsefod' *Chenopodium album* (hard to distinguish from quinoa) and 'snerlepileurt' *Fallopia convolvulus* (hard to separate). Aphids are a problem; they are controlled when quinoa is flowering.

What inputs are needed for production? Quinoa can be produced organically, for example with clover grown before, although it grows best after oats. (IB:) Also more cultivars are needed, so far only a few are used. (CH:) Approved control methods are needed, both for conventional and organic control of biotic problems.

Do you think there will be more production in Denmark in the future? It depends on the price a farmer can get, but due to the cost of cleaning and processing, higher prices would be needed to make it worthy for the farmer. (IB:) The access to the local market is not easy; consumers still prefer to buy quinoa coming from South America. (CH:) Quinoa is already growing in Denmark and as there is more interest in protein crops, perspectives for it would be that the production area keeps increasing.

Which challenges do you see for the production of quinoa? The challenges are not production related, it is just the problem of selling the quinoa. There is a lack of facilities for processing quinoa in Denmark. If farmers could sell their seed to companies such as DLF, that would be better.

Do you eat quinoa yourself? Not often - I eat it once or twice a year.

11.3 Evolution and Perspectives of Quinoa in Research

11.3.1 Research in the Andean Region

Contemporary research into quinoa in the Andean region began in the 1940s, and established the basis for further, global, research in quinoa. In the 1960s, researchers across the Andean region began collection, characterisation and conservation of local germplasm, plant breeding and research into nutrition, uses and processing of quinoa (Tapia 2014).

A relevant activity in the development of research into quinoa was the first international quinoa workshop, which took place in 2001 in Lima, Peru. This led to a succession of International Quinoa Conferences, and a dramatic increase in the production of quinoa globally (Tapia 2014).

Further growth in quinoa production outside of the Andean region was generated by the United Nations International Year of Quinoa (IYQ), in 2013. The aim of this, according to the FAO, was the 'recognition of ancestral practices of the Andean people' (FAO 2019). A large number of activities were held, from festivals, cooking contests and tasting events to exhibitions, seminars and scientific conferences, alongside the global dissemination of recipes, articles and information about quinoa.

Recent research has included socio-economic studies of the quinoa production chain, conservation of germplasm, molecular analysis, development of products and determination of nutritional value. Breeding has focused on adaptation to climate change (later and shorter rains), resistance to mildew and drought, precocity, as well as grain colour and size, leading to the release of new cultivars (Gandarillas et al. 2014; Tapia 2014).

11.3.2 Research in the Rest of the World

There has been growing interest in quinoa globally over the last few decades, due largely to the high nutritional properties, in particular the quality of protein and lack of gluten. It is also attractive due to its high genetic diversity and adaptability to various climate and soil types.

In Europe and the United States, demand for quinoa has rapidly increased over recent decades. The research focus has been on adapting varieties to longer days and short summers (Jacobsen 2003), reducing saponin content in the seed coat and increasing quinoa's abiotic tolerance mechanisms (Bazile et al. 2016b).

In China, there have also been significant investments into the development of quinoa, particularly in the north of the country (Xiu-shi et al. 2019). On the Indian subcontinent, quinoa is potentially part of a solution to increasing agrobiodiversity and spreading farmers´ risks, as well as a source of protein, although it is still in research stages there (Bhargava and Ohri 2014).

The first quinoa experiments outside of the Andes were in 1935 in Kenya (Bazile et al. 2016b). Across Africa, there is increasing research into quinoa as a crop with potential in drought- and salinity-prone areas (Bazile et al. 2016a) . Quinoa is seen as a crop with high potential in areas of food insecurity and malnutrition, due to the high-quality nutrition that quinoa provides. The main issues for further research have been identified as: acceptability by consumers, best management practices for small-scale farmers and selection of suitable cultivars for different conditions (Maliro and Guwela 2015).

In the Middle East, particularly in Morocco and the UAE, research has focused on quinoa's drought and salinity resistance, for production on marginal land. While yields remain low, the production area is increasing steadily, and beginning to spread further in the Middle East and Central Asia (Choukr-allah et al. 2016; Rodriguez et al. 2020).

11.3.3 Perspectives

Several studies targeted abiotic stress in quinoa, this plant represents a good model to understand the processes and pathways of stress responses. Innovation and research will keep developing this line to keep giving solutions for climate change and provide information towards breeding strategies. Considering the trends of dissemination of quinoa around the world, efforts in research will concentrate in developing new genetic materials for the regions with high potential to grow quinoa. Different technologies might be used for that, such as mixed breeding techniques as it is done in Germany (Kiel University 2018) or novel genomic tools starting to develop in Denmark (Palmgren 2019). Moleculars tools keep in use to characterise the diversity of quinoa collections. Now with the recent quinoa genome description, the identification of genes will be targeted for sources of tolerance for abiotic and biotic stress with the use of traditional and modern phenotyping tools (Jarvis et al. 2017; Tester 2019). From the nutritional side, several studies have described the qualities of quinoa from different points of view such as the recent descriptions of quinoa as a functional food. More investment in the food area will be addressed to develop quinoa as an ingredient for different food products.

Wild species in quinoa production systems, Bolivia

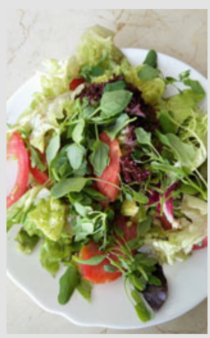
The Bolivian research Foundation PROINPA has recently undertaken research into quinoa interactions with native wild legume and grass species. These provide protection from erosion, fix nitrogen and provide other nutrients for quinoa, wild legume species can also be used as a forage source and in traditional medicine. PROINPA aims to reintroduce these wild species to quinoa production systems, making use of local ancestral knowledge, as well as preserving these species and replicating their interactions with quinoa plants in the wild.

Wild lupin, *Q'ila-q'ila,* is a native legume, which can tolerate frost and drought, and grows well in sandy soil. PROINPA is investigating this in a rotation with quinoa, to provide biomass to the soil and fix nitrogen.

Other wild species can act as natural barriers. These include shrubs such as *Lampaya* and Thola thola (*Parastrephia lepidophylla*), and grasses such as *Nassella*, *Festuca* and *Stipa* spp. These living barriers help to reduce the wind speed and the loss of soil, thus protecting the quinoa plants. However, their numbers have been reduced due to the increase of the agricultural land area. PROINPA therefore is promoting their use (Fig. 11.4).

Other species are being promoted for their use as fodder for camelids, traditionally raised in the quinoa-camelid production system in southern Bolivia. Ideally, two or three llamas per hectare would produce manure to benefit quinoa production (Bonifacio et al. 2013).

El-Samad et al. (2018) investigated in Egypt the potential use and the nutritional value of quinoa as a leaf crop comparable to spinach. They found that while spinach had higher contents of fibre and carbohydrates, as well as nitrite and nitrate, quinoa leaves had higher content of fats, proteins, antioxidants and higher levels of nitrogen, potassium, calcium and manganese. However, the nutritional value of quinoa leaves could be different depending on cultivars. Despite this, the authors recommend that quinoa leaves could be a good source of proteins, minerals and vitamins since they can grow with minimal input and could be beneficial to communities living on marginal soils and saline water.



Quinoa as a leaf vegetable, Egypt (Photo credit: J.P. Rodriguez)

While quinoa grains are commonly incorporated into different kinds of breads and

Fig. 11.4 Seed collection and implementation of living barriers and production areas with native legume and grass species (photo credits: G. Alandia)

cakes, new research is investigating whether quinoa leaf would be a good addition. Tests found that while the leaves improve the antioxidant levels in bread, they may alter the quality of the bread negatively, in particular the protein digestibility (Świeca et al. 2014).

This study is one of very few investigating quinoa leaves as a vegetable crop, but it suggests that they could have great potential in the future.

Fig. 11.5 Traditional practices, uses and consumption of quinoa in Bolivia: **(a)** Bulk sale of quinoa, **(b)** milling the grain with stone, **(c)** local products selling and **(d)** consumption (photo credits: J.P. Rodriguez)

11.4 Evolution and Perspectives of Quinoa for Food

11.4.1 In Food and Market

Quinoa has been traditionally consumed in the Andean countries, in whole grain preparations including porridges, beverages and soups (Fig. 11.5). The grains are also processed into flours for bread, traditional meals, or toasted flour for snacks and beverages. More recently, industries have started to include quinoa as an ingredient in snacks, for example, extruded quinoa for breakfasts or muesli bars, flours for pasta, cookies, instants soups, pre-cooked quinoa, beer and diverse other products for export (Fig. 11.7). However, the predominant export has been as a raw grain to retailers for processing abroad.

In fact, quinoa development in the Andean countries has been a direct response to demand. The rise of the diet-food market in the 80 s, the organic market in the 90 s, the fair trade market in the 2000s and the promotion of the IYQ in 2013 gave rise to the evolution of this crop in Bolivia and in the Andean region (Fig. 11.6).

Production progress from 1961 to 2015 can be observed in Fig. 11.6. In the 1980s quinoa was established in more areas of Bolivia, Peru and Ecuador, compelled by policies that promoted this grain and the association of producers who started to introduce quinoa to the market. Later in the 1990s the traditional quinoa produced in the Southern highlands of this country fitted well for the organic market and later in the 2000s in the fair trade market. Finally, with the promotion activities motivated by the Bolivian government and the United

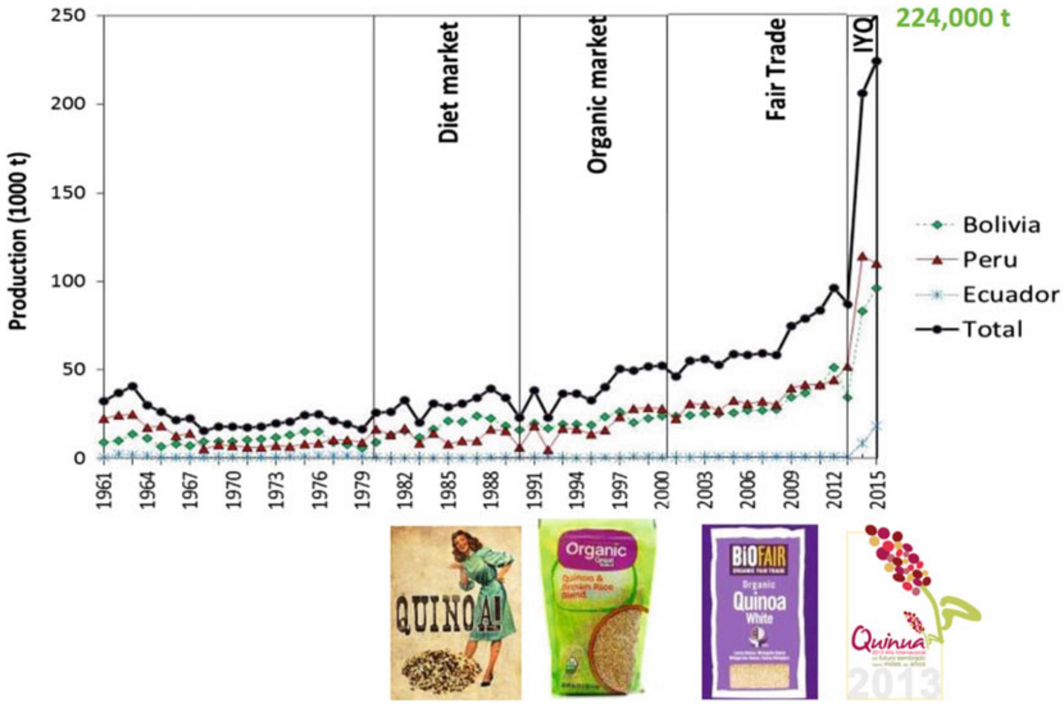


Fig. 11.6 Evolution of quinoa production in the Andean region (*source* elaborated with data from: Alandia et al. 2020)

Nations (UN) through FAO and the IYQ, the demand reached levels that the country was unable to fulfil even with increased areas of production. By 2015, Bolivia produced 60,000 tonnes of quinoa. Similar development happened in Ecuador on a smaller scale and in Peru with higher technology producing a total of 224,000 t in the Andean region, as it is shown in Fig. 11.6.

Nowadays, quinoa is included in many food products; not only in the traditional countries of production but also in several countries where production has begun recently. It started being consumed and purchased as grain, and then progressively the industry started to produce and provide flour, flakes, extruded quinoa for muesli or energy bars. It is now possible to find a diverse range of products with quinoa in different markets globally (Fig. 11.7).

11.4.2 In Healthy Diets and Food Safety

Quinoa has great qualities as a food. It is well known that this grain has a protein content ranging between 12–20% and that it contains all the essential amino acids. Nutritionally it has been compared to dried whole milk (Vega-Gálvez et al. 2010). The body is able to absorb 73% of the protein present in quinoa (a variable known as biological value); this value is similar to the biological value in beef (74%) and higher in relation to other grains (rice, wheat and corn range between 36 and 56%) (Gordillo-Bastidas et al. 2016).

Quinoa is also rich in minerals that are important for body structure and functions, such as calcium for bones and iron for blood. Quinoa also contains zinc, which supports the immune system, as well as magnesium, vitamin E, vitamin B

Pre-cooked quinoa with curry mushrooms and vegetables (CH)
Cost: € 1.62

Multicereal pasta with quinoa (SP) Cost: € 1.69

Cooked quinoa ready to eat (DK)
Cost: € 2.3

Different quinoa products in a supermarket shelve (MX)
Costs: between €2.5 – 10.6

Malta drink with quinoa (BO)
Cost: € 0.9

Multi-fibre cookies with quinoa (AE)
Cost: € 5.32

Fig. 11.7 Different products with quinoa found in different parts of the world. *Note* In parenthesis Alpha-2 ISO country codes (for Chile, Spain, Denmark, Mexico, Bolivia and the United Arab Emirates). All prices correspond to the year 2019. Photo credits: G. Alandia, L. Robles and J.P. Rodriguez

complex, tryptophan amino acid and omega fatty acids, which are relevant for the nervous system. In addition, it is free of gluten, which can cause small intestine inflammation reactions in patients with celiac disease (Gordillo-Bastidas et al. 2016). Finally, quinoa has a low glycemic index (GI) that ranges 35–53 and puts quinoa in the list of food options to reduce the risk of type 2 diabetes.

These functional qualities mean that quinoa is a great addition to diets addressing specific health needs, such as gluten-free and low glycaemic diets. Due to the high bioavailability of its amino acids and the quality of its nutritional components, quinoa represents a good alternative in healthy diets in particular for young children and the elderly.

Economic wealth and education influence personal choices. When these factors are present, people tend to choose more healthy and safe products. These include more natural and less processed products as well as foods enhancing health, such as functional foods. Quinoa comes from traditional production systems and there are sectors of people from growing economies willing to pay for exotic and/or less processed products.

11.4.3 In the Plant-Based Food Sector

The meat alternative industry is growing fast; in fact, financial analysts predict that in ten years, this new sector could replace 10% of the global meat industry (USD 140 billion) targeted by companies such as Beyond Meat, Impossible Foods and Nestle (Franck 2019). Companies such as Danone also project that they will triple their plant-based sector revenues to more than €5 billion by 2025 with products such as plant-based yogurts and ice cream (Gretler 2019). Supermarkets are diversifying their offers in order to meet the demand for meat alternatives. Last year, the UK chain Sainsbury's expanded their range of plant-based products by 35% (Chiorando 2018). The demand for plant-based dairy products is increasing and different products are offered based on soybeans, rice, almonds, oats and in some countries also quinoa. The bakery industry represents an important market for quinoa. Quinoa can be included in different type of products: as food, as an ingredient (grain, flour, flakes) and as protein concentrates, fractions, extracts and isolates.

11.4.4 For Environmentally Responsible Consumption

Countries have promised to concentrate efforts on reducing greenhouse gas emissions and building climate resilience. Agriculture and food constitute important targets to achieve this. Therefore, regions and countries have agreed to build more energy efficient food systems and reduce meat intake in people´s diets to make consumption and production patterns more sustainable. Activities to catalyse the change of diets and food systems are under development to achieve the Sustainable Development Goals (SDGs) for 2030 (United Nations 2015). These include regional and local programmes, projects and funding. The development of all concerned food sectors is taking place gradually.

Diets are changing and responsible consumption is turning people's interests towards flexitarian, vegetarian and vegan diets that reduce or replace meat consumption with alternative-protein food. Quinoa is a good alternative to generate high-quality plant protein food. It has been widely accepted by consumers and in addition, it has carbon and water footprints 30 and 60 times lower than beef (Gordillo-Bastidas et al. 2016).

11.4.5 Perspectives

Consumer demand for quinoa will continue to rise in the coming years, as trends towards healthy foods or climate responsible consumption increase, in particular for plant proteins or diversifying diets as described above. Particularly in the developing world, quinoa provides the possibility to feed more people in fragile areas. In the other hand, markets are specialising and are demanding not only white large seeds, but also other seed colours such as red, or black. For further increase of quinoa production, the facilities to process and transform this grain need to develop in parallel in the new areas where this grain will be implemented.

11.5 Challenges

In order for quinoa production to successfully continue to increase, it has to face a number of challenges, both in the Andean region and in the rest of the world.

Biotic stress resulting from pests and diseases must be addressed to ensure that yields meet their potential. More studies are needed in the areas of plant pathology and entomology in order to identify emerging problems with biotic agents that will keep in rise with climate change. Research continues to advance with downy mildew (*Peronospora variabilis* Gäum), which is the most reported disease in quinoa, but still more can be done to find sources of tolerance to the crop and provide control options applicable to the new countries of production and farming systems. The same situation exists for pests such as aphids (*Aphis* spp), flea beetles (*Phyllotreta* spp) and many other organisms that may appear with the introduction of this crop in different regions. The establishment of monitoring systems at different scales (global, regional, local) to record the emergence of biotic agents will be needed to keep developing this crop. Collaborative work would be a good way to target this to make reality an international research centre for underutilised grains situated in the Andes like it has been done with potato at the International Potato Center (CIP).

There is a need for development of cultivars adapted to different conditions. Quinoa has a huge genetic diversity and has the potential to adapt to many environments and requirements, due to the diverse ecotypes it originates from (Bazile et al. 2016a). In future, breeding efforts can further develop these characteristics to adapt them to the specific needs of different regions. For example, day length, light levels, soils, altitude and heat. In dry areas, the challenge is testing varieties of quinoa that are already tolerant to drought conditions and improving them to adapt to other types of stress such as heat. In Europe and North America, quinoa must be early maturing, in order to adapt to short summers, but this is also helpful in South America in order to address the gradual reduction of the rainy season. Collaborations between breeding programmes can therefore be helpful in achieving the different aims and interests in quinoa globally.

The global impact of quinoa's rise must also be considered in future, in the case of quinoa and with new-emerging crops. Nuñez de Arco (2015) highlights the paradox of the United Nations intention to provide affordable quinoa to the poor, while also lifting many small quinoa farmers out of poverty—a drastic fall in prices means that one is satisfied, but not the other. A recommendation to bodies such as the FAO is that events like the IYQ should integrate the whole process of promoting and increasing demand to ensure a sustainable and stable supply, in order to avoid price collapses that directly affect farmers, as happened in 2014 (Alandia et al. 2020).

Another breeding aim is to further reduce the saponin content of the seed, therefore reducing bitterness. If bitter materials are used, then processing facilities need to be developed to clean the saponins from grains. However, these are expensive and not available in countries starting to produce this grain.

Farming systems adopting quinoa in the future must use adequate technology in order to be able respond to the market demand, but also avoid unsustainable practices. The quinoa boom in the early 2000s raised the question of sustainability due to high demand and the negative effects of extensive and intensive quinoa production on the land of the main exporting countries of South America (Peru and Bolivia). The expansion of the agricultural frontier and unsustainable practices to achieve the demanded production raised social and environmental concerns.

Challenges with genetic material

The ethics of the sharing of genetic materials by Andean countries is also in question. The traditional quinoa-producing countries face tough competition and may lose markets due to the production of quinoa outside the Andean region. However, this is not necessarily with recognition of the origin of the genetic material, the seed property rights, or the equitable distribution of benefits derived from the use of the genetic resources. Currently the development of new cultivars is possible outside of the Andean region without any sharing of benefits or recognition with the region of origin of the genetic material. Quinoa is not included in the system of multilateral exchange, which would protect the biological origin of quinoa taken outside the Andean region (Rojas et al. 2015; Bazile et al. 2016b). The enormously diverse genetic material for quinoa has been developed over thousands of years in the Andes, and for Andean countries to benefit of this, the existing legal framework must be revised and built upon. Intellectual rights protections and recognitions can help to ensure that quinoa farmers also benefit. Better dialogue at all levels of quinoa use is required, in order to better connect farmers, researchers, breeders and politicians, which is necessary for quinoa's future (Alandia et al. 2020).

Furthermore, quinoa breeding outside of the Andean region is limited, as it is dependent on a reduced quinoa biodiversity available in collections established prior to the protective agreements of 1992 and 2004 (the Convention of Biological Biodiversity and the International Treaty on Plant Genetic Resources for Food and Agriculture respectively) (Alandia et al. 20).

11.6 Conclusions and Recommendations

Quinoa is an Andean grain with high nutritional quality and that has recently been qualified as a super-food. This grain, with high biological value, contains high-quality proteins including all the amino acids essential for human nutrition. It has omega acids that benefit health and a glycaemic index (GI) that make it eligible as a great candidate for the new diet trends. Quinoa can also be considered as a super-crop. It can grow under extreme climates and soils where most other crops would fail, and it is particularly useful in areas of drought and salinity. It is due to this combination of benefits that interest in quinoa has risen so drastically over the last few decades. However, such a boom cannot arise without costs. In order to maintain quinoa as a superfood and super-crop in the future, some things must be taken into consideration, in particular the effects in South America.

Firstly, to ensure that future breeding programmes are able to satisfy the demand for new varieties of quinoa which are adapted to different climates and soils, the diverse genetic material originating in South America must be recognised when it is taken out of the area. This could be done within a revision of the existing legal framework, that makes effective and tangible the acknowledgement and compensation to those who have conserved or bred the parental materials. Investment is needed in agricultural research around the world, for example for innovating agricultural techniques, new processing technologies, or to study and ensure the application of positive local/traditional sustainable production practices. Learning from the past and collaborating at different levels (locally, regionally, globally) may be the way forward for a sustainable development of this grain. And finally, we should promote the consumption of quinoa and other plant proteins to reduce the climate footprint, protect our environment and ensure future climate resilient agricultural systems.

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