Utilisation and limitations of pseudocereals (quinoa, amaranth, and buckwheat) in food production: a review

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Utilisation and limitations of pseudocereals (quinoa, amaranth, and buckwheat) in food production: a review

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Abstract:	Background Pseudocereals, especially quinoa, amaranth, and buckwheat, have attracted an increasing amount of attention because of their nutritive and health-benefiting properties, and their suitability for people suffering from coeliac disease and gluten intolerance. However, the utilisation of pseudocereals is hampered by the presence of anti-nutritional compounds (phytates and saponins) and/or substances that yield a bitter taste in the seeds, the latter of which must be minimised before or during food processing, consequently increasing the cost and risk of environmental contamination. Scope and approach The objective of this review is to analyse issues relating to the use of pseudocereals in food production, including: i) technological limits in the food industry; ii) agronomic limitations to pseudocereal cultivation and distribution; iii) technological and biotechnological tools for addressing these issues; and iv) socio-economic and ethical implications of extensive cultivation. Key findings and conclusions Although pseudocereals have great potential for use in the food industry, they cannot completely replace true cereals due to the presence of compounds that confer undesirable organoleptic and technological characteristics to their products. As the growth in pseudocereal cultivation, especially that of quinoa, remains largely restricted to the nations in which the pseudocereals originated, it is imperative that the excessive exploitation of resources be avoided in these areas. Moreover the improvement of the socio-economic conditions of small farmers is necessary, since they manage the germplasm of these species. Biotechnologies are valuable tools for exploiting the considerable diversity of these species for breeding programs aimed to improve palatable, technological and agronomic characteristics.
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Response to Reviewers:	One sentence paragraph (Line 78-80) is combined with the previous paragraph (line 77) to be one paragraph. Done (lines 77-80) Line 124-140 (3 paragraphs) are combined into one paragraph (to avoid 2 paragraphs consisting of 1 sentence). Done (lines 123-138).

	Put an indent in Line 144, 182, 192, 202 to indicate these as new paragraphs. Done (lines 142, 180, 191, 201) Line 208-211 are combined with the following paragraph in Line 212 to be one paragraph. Done (lines 207-221) Line 247-249 are combined with the following paragraph in Line 250 to be one paragraph. Done (lines 245-256) Put an indent in Line 262 and 270 to indicate these parts as two new paragraphs. Done (lines 259, 267) Put an indent in Line 323, 345, 376 to indicate them as new paragraphs. Done (lines 320, 342, 373) Line 411-413 are combined with the previous paragraph in Line 410 to be one paragraph. Done (lines 407-410) Line 415-424 (3 paragraphs) are combined in one paragraph (to avoid 2 paragraphs consisting of 1 sentence). Done (lines 412 -421) Line 436-461 are combined in one paragraph. Done (lines 433-456)

Dear Prof. Oey,

thank you for your suggestions. We have merged paragraph and put indent as you have suggested (see answers to reviewers).

We hope that the manuscript in its revised form may now be suitable for publication in ‘Trends in Food Science and Technology’.

Thank you again for the kind attention to this paper.

Best regards

Caterina Agrimonti

One sentence paragraph (Line 78-80) is combined with the previous paragraph (line 77) to be one paragraph. **Done (lines 77-80)**

Line 124-140 (3 paragraphs) are combined into one paragraph (to avoid 2 paragraphs consisting of 1 sentence). **Done (lines 123-138).**

Put an indent in Line 144, 182, 192, 202 to indicate these as new paragraphs. **Done (lines 142, 180, 191, 201)**

Line 208-211 are combined with the following paragraph in Line 212 to be one paragraph. **Done (lines 207-221)**

Line 247-249 are combined with the following paragraph in Line 250 to be one paragraph. **Done (lines 245-256)**

Put an indent in Line 262 and 270 to indicate these parts as two new paragraphs. **Done (lines 259, 267)**

Put an indent in Line 323, 345, 376 to indicate them as new paragraphs. **Done (lines 320, 342, 373)**

Line 411-413 are combined with the previous paragraph in Line 410 to be one paragraph. **Done (lines 407-410)**

Line 415-424 (3 paragraphs) are combined in one paragraph (to avoid 2 paragraphs consisting of 1 sentence). **Done (lines 412 -421)**

Line 436-461 are combined in one paragraph. **Done (lines 433-456)**

Highlights

- Antinutritional compounds limit the exploitation of pseudocereal in food industry.
- Agronomic factors limit the cultivation outside the original countries
- Exploitation of pseudocereals should be ethical and sustainable
- Biotechnologies and genomics are tools to improve useful traits

Abstract

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Key words: quinoa; buckwheat; amaranth; cereal-based foods; technological improvement; sustainability

Introduction

Pseudocereals are dicotyledonous species that produce seeds with a starch content and physical appearance similar to those of true cereals. The seeds of pseudocereals can be ground to produce flour for pasta and bakery goods, but they do not contain gluten. The most popular pseudocereals are quinoa (*Chenopodium quinoa* Willd), amaranth (*Amaranthus* L. spp.), and buckwheat (*Fagopyrum esculentum* Moench and *Fagopyrum tataricum* (L.) Gaertn) (Pirzadah & Malik, 2020).

The cultivation of quinoa dates back to 5000–3000 BC in the Andes region of South America. The Incas considered quinoa to be a sacred food up until the time of Spanish colonisation, at which point true cereals were adopted (Angeli et al., 2020). Quinoa production has increased steadily over the past decades, with production and consumption increasing exponentially after 2013 (Hunt et al., 2018). In 2019, quinoa cultivation encompassed 184,585 hectares, mainly in Bolivia, Peru, and Ecuador, with production reaching 161,415 tons (http://www.fao.org/faostat/en/#data/QC) (Figure 1A).

Buckwheat originated in the southwest of China, from the mid-6th millennium BC, outside of the major agricultural centres associated with rice and millet. It then spread to Europe from around the 3rd millennium via trade routes connecting the southern Himalayas to the Caucasus and Europe (Hunt et al., 2018). In 2019, buckwheat cultivation covered 1,673,478 hectares worldwide, with the production of approximately 2,042,401 tons (http://www.fao.org/faostat/en/#data/QC). Globally, the Russian Federation (46.72% of global production) and China (29.73%) are the primary producers, followed by the USA (4.77%), Ukraine (4.13%), Kazakhstan (4.03%), and Japan (3.90%) (Figure 1B).

Amaranthus spp. are native to Central and South America with the exception of some species, such as *A. spinosus* L., which grow in tropical and subtropical regions of India. Amaranth was a staple food of the Maya and Aztecs of Central America, but consumption fell to negligible levels following European colonisation (Tömösközi et al., 2011). Although amaranth production is not officially recorded by the UN's Food and Agriculture Organisation (FAO), key producers include several South American countries, along with China, India, Russia, and Kenya (Aderibigbe et al., 2020).

Interest in pseudocereals has emerged largely because they are rich in numerous compounds with beneficial properties for human health, including proteins, peptides, flavonoids, phenolic acids, fatty acids, vitamins, amino acids, dietary fibres, lignans and unsaturated fatty acids, among others (Martínez-Villaluenga et al., 2020; Pirzadah & Malik, 2020) (Table 1). In addition, pseudocereals show great promise in the production of gluten-free (GF) foods, with interest driven by the rise in dietary choices in which gluten is considered an unsafe ingredient, and by the need to identify alternatives to gluten-rich foods for individuals who suffer from coeliac disease, wheat allergies, or non-coeliac gluten sensitivity (Graziano et al., 2019). Given the increase in frequency of these pathologies in developed countries, wider use of wheat-alternative cereals (rice, maize, sorghum, and others) is critical. Projections indicate that GF food production will expand at an annual growth rate of 9.1% from 2019–2025 (Martínez-Villaluenga et al., 2020). However, GF foods are usually higher in fats, sugars, and sodium and lower in protein, minerals, and fibres than gluten-rich foods; as such, pseudocereal seeds offer great potential in supplementing the nutritional deficiencies of a typical GF diet (Cornicelli et al., 2018).

Moreover, the exploitation of pseudocereals for food production, reduces the narrow crop rotation increasing crop availability and diversity. In addition, it provides foods with novel properties for meeting worldwide nutritional needs, thereby fulfilling several objectives of the UN's Agenda 2030, such as elimination of hunger, achieving food security, improving nutrition, and promoting sustainable agriculture (sdgs.un.org/2030agenda).

However, the efficient exploitation of pseudocereals is limited by several technological factors. The lack of a gluten network confers negative characteristics to foods, such as hardness in breads and loss of cooking capacity in pasta (Haros & Sanz-Penella, 2017), while the high phenol content of pseudocereal seeds confers a bitter taste (Suárez-Estrella et al., 2018). Moreover, seeds often contain high concentrations of phytates, saponins, and other compounds that impair their nutritional properties (Suárez-Estrella et al., 2018). Other concerns have also arisen over sustainability and ethical implications, particularly with regard to quinoa which has seen a doubling of the land used for its cultivation over a decade (from 2010 to 2019). In Bolivia, for example, expansion of quinoa cultivation has led to increased rates of deforestation, exacerbating soil erosion (Jacobsen, 2011).

Our primary objective here is to review issues associated with the utilisation of pseudocereals in food production, particularly that of quinoa, amaranth, and buckwheat. After the description of beneficial properties of these pseudocereals, we will focus on: *i*) technological limits in their utilisation for food production (in particular bakery products and pasta) *ii*) agronomic limitations to pseudocereal cultivation and distribution; *iii*) potential technological and biotechnological tools for addressing these issues (genetics and "omics" resources); and *iv*) socio-economic and ethical implications of extensive cultivation, especially with regard to indigenous populations.

Bioactive compounds and their beneficial properties for human health

The wide use of pseudocereals in food products is due to their good nutritional value and the presence of bioactive compounds in grains (Table 1). They contain more lysine, methionine, and cysteine than common cereals as well as starch, fibres and proteins. Furthermore, pseudocereals contain many bioactive compounds, such as saponins, phenolic compounds, phytosterols, phytoecdysteroids, betalains and bioactive proteins and peptides. These compounds, in particular, flavonoids, phenolic compounds and peptides, have several beneficial effects on human health, which we will discuss along with antioxidant capacity. Phenolic compounds are present in three forms: soluble-free, soluble-conjugated to sugars or other molecules, and insoluble-bound forms (Martínez-Villaluenga et al., 2020).

In quinoa seeds, the three forms of polyphenols vary in concentration, ranging between 167.2–308.3 mg gallic acid equivalent/100 g dw, while free polyphenols are more plentiful, comprising 53.5%–78.0% of the total polyphenol content (Han et al., 2019). Gallic and ferulic acids are the most abundant compounds, followed by flavonoids (Martinez-Villaluenga et al., 2020) of which rutin, quercetin, and kaempferol (free fraction) are the most common. Bound phenolic compounds are present at lower concentrations (Rocchetti et al., 2019; Martinez-Villaluenga et al., 2020). In contrast, buckwheat is a good source of phenolic compounds (275.5–532.0 mg gallic acid equivalent/100 g dw) (Rocchetti et al., 2019; Martinez-Villaluenga et al., 2020), whereas amaranth has the lowest levels of phenolic compounds of the three (21.2–57 mg gallic acid equivalent/100 mg dw), consisting primarily of ferulic acid, flavonoids, sesamin, tyrosol, and cardol (Rocchetti et al., 2019).

Grains of quinoa, amaranth, and buckwheat all have high concentrations of proanthocyanidins (PAs), which are oligomeric flavonoids that possess anti-inflammatory, antioxidant, anticancer, and antidiabetic properties (Thakur et al., 2021) (Table 1). All three species are a good source of proteins that can generate bioactive peptides, with beneficial effects on human health, including antioxidant properties. These peptides have been identified in hydrolysates, gastrointestinal digests, and fermented products, although their specific functional properties depend on the degree of hydrolysis, amino acid composition, and protein structure (Martinez-Villaluenga et al., 2020; Morales et al., 2021). The antioxidant properties of peptides are due to different mechanisms, such as inactivation of reactive oxygen species, scavenging of free radicals, metal chelation, and reduction of hydroperoxides; as a consequence, their addition to food may have a beneficial effect toward the prevention and treatment of diseases related to oxidative stress. Additional and detailed information about beneficial health properties is provided in more recent reviews (Morales et al., 2021; Thakur et al., 2021). However, evidence of the beneficial effects on human health of the compounds mentioned above has largely been evaluated in cellular models, with few *in vivo* animal studies or clinical trials available to assess the full range of positive health effects (Martinez-Villaluenga et al., 2020; Morales et al., 2021; Thakur et al., 2021).

Technological limits in the utilisation for food production

Antinutritional and undesirable compounds in pseudocereals, and potential treatments

Along with their beneficial properties, pseudocereals contain several anti-nutritional compounds, such as saponins and phytates, as well as molecules that may have detrimental effects on the organoleptic properties of derived foods. Specific treatments are required to remove these undesirable compounds (Table 2).

Quinoa seeds contain pericarp saponins that confer a bitter taste to the resulting products, and may reduce zinc and iron absorption (Filho et al., 2017). Saponins have positive characteristics, such as anti-hypercholesterolemic, analgesic, anti-allergic, and antioxidant properties, but they also reduce vitamin bioavailability and food conversion efficiency, and can damage cells of the small intestine mucosa (Suárez-Estrella et al., 2018). Treatments to remove saponins include washing, pearling, fermentation, and germination. In rural areas, washing is the most commonly employed method because saponins are soluble in water. Seeds are dried immediately after washing to prevent germination and mould growth, with a consequent increase in cost (Pappier et al., 2008); in addition, wastewaters rich in saponins may pose an ecological hazard (Suárez-Estrella et al., 2018). Pearling, an abrasion technique that removes the outer layers of seeds, is more efficient than washing because it does not require additional drying treatments and has a limited impact on the environment, but it may reduce phenol, fibre, and mineral content (Gómez-Caravaca et al., 2014). In many areas, a combination of washing and pearling is often used (Suárez-Estrella et al., 2018).

Seed germination exploits sugar production, which helps to mask the typical bitterness of pseudocereals. However, standardisation is required for optimising the temporal and environmental conditions to improve sugar content without affecting other beneficial properties (Omary et al., 2012)

Amaranth flour is rich in Cu, Mn, Zn, Fe, Ca, Mg, P, and K, but it also contains phytates that limit their absorption (Sanz-Penella et al., 2013). Although several strategies have been adopted to reduce the phytate content in pseudocereals, such as soaking, malting, and germination, which can activate seed phytases, these have proven to be ineffective (Rollán et al., 2019). One promising strategy is lactic fermentation, which exploits the phytase activity of some lactic acid bacteria (LAB) naturally present in pseudocereals (Rizzello et al., 2016; Rollán et al., 2019). The use of quinoa sourdough supplemented with *Lactobacillus plantarum* and *L. rossiae* significantly increased phytase activity when compared to that of non-fermented flours. Moreover, animals fed pasta made with quinoa flour enriched with LAB-produced phytase had higher hepatic concentrations of P, Ca, Fe, and Mg than control animals (Carrizo et al., 2019)

Buckwheat should be dehulled before grinding because the hull is non-digestible (Dziedzic et al., 2016). Hulls adhere to seeds, requiring aggressive thermal or non-thermal treatments for their removal. Seeds are subjected to steam heating at 150–160°C during thermal treatment, whereas for non-thermal treatment they are simply immersed in water and dried until the hull breaks. Thermal dehulling reduces total phenolic content, but increases the content of quercetin and hydroxybenzoic acid, and prevents *Aspergillus flavus* infection and aflatoxin contamination. Therefore, thermal treatment is preferred to preserve the safety of buckwheat products, especially when grains are stored for long periods of time (Pandey et al., 2020).

Roasting is the principal treatment in the creation of buckwheat products (groats, bran, roasted grains, and roasted hulls). It increases the content of some phytosterols, such as camposterol, sitosterol, avenasterol, D-7 stigmasterol, and cycloartenol, in grains and groats, but reduces the content of stigmasterol, which is a thermolabile compound (Dziedzic et al., 2016). It is likely that high temperature and pressure promotes sterol ester hydrolysis, thereby increasing phytosterol content (Fernandes & Cabral, 2007). However, thermal treatments generally reduce the availability of useful molecules, particularly flavonoids; therefore, caution should be taken in terms of treatment temperature and duration to preserve the nutritional properties of buckwheat (Tian et al., 2014).

Technological and organoleptic properties of food derived from pseudocereals (bakery and pasta)

Pseudocereals are common ingredients in many traditional dishes of indigenous peoples, including soups, porridges, tortillas, and both alcoholic and non-alcoholic beverages. In modern times, the use of pseudocereals has expanded considerably and now encompasses bakery items, pasta, dairy substitutes, and seasonings, among others (Table 2). In particular, quinoa, amaranth and buckwheat offer the opportunity to enrich the flours employed in baked foods and pasta and to overcome the gluten problem for celiac and otherwise gluten-intolerant people. This use of pseudocereal flours requires specific studies to characterise their effects on the technological and organoleptic properties of the derived products. For this reason, in the following paragraphs, we will focus on these categories of foods.

Bakery items and pasta

Quinoa is used to make pasta, bread, and other bakery products. In general, its addition to wheat flour improves the nutritional properties of bread (higher fibre, mineral, protein, and healthy fat contents), but reduces volume, increases hardiness, and confers a dark colour and bitter taste (Haros & Sanz-Penella, 2017). These negative characteristics depend on the percentage of quinoa flour; at concentrations up to 25%, they were not perceived, whereas consumers reported increased hardness at a concentration of 50% (Iglesias-Puig et al., 2015).

Proportions of 15–25% quinoa flour increase the content of polyphenols and antioxidant properties in dough, but these characteristics are lost during baking (Ballester-Sánchez et al., 2019; Xu et al., 2019); the use of flour derived from germinated seeds can also reduce bread hardness and bitterness (Suárez-Estrella et al., 2020). Similarly, the addition of quinoa flour improved the nutritional properties of pasta, but reduced textural and sensory properties, and increased phytate and saponin content (Demir & Bilgiçli, 2020). Flour obtained from germinated seeds had higher protein and amino acid contents, and lower amounts of phytate, with consequent loss during cooking; there was also reduced pasta firmness (Demir & Bilgiçli, 2020). Pasta properties depend on the quinoa variety; flour from Peruvian natives (var. *rosada taraco*, *kuchivila*, *negra collana*, and *mistura*) and Latvian-grown (var. *titicaca*) varieties, independently incorporated into buckwheat flour at a 20% proportion, affected pasta characteristics in different ways. Pasta containing var. *negra collana*, which has the highest fibre and lowest saponin contents, was structurally strong (high cohesiveness and firmness), whereas pasta containing var. *titicaca* and *kuchivila* were structurally weak in comparison. However, adding var. *taraco* and *mistura*, varieties with high saponin contents, improved pasta structure with little effect on taste (Ramos-Diaz et al., 2020).

Bread baked from dough supplemented with amaranth flour had higher nutritional contents (higher fibre and mineral contents, including Ca, Fe, and Zn, and fewer carbohydrates) than bread made with 100% wheat flour, but they also had smaller volumes, a harder crumb, darker colour, lower acceptability, and higher tannin and phytate contents (Miranda-Ramos et al., 2019; Mukhtar et al., 2020; Ramos-Diaz et al., 2020; Zula et al., 2020). The ideal percentage of amaranth flour remains under debate, with Zula *et al*. (2020) reporting acceptable parameters of up to 40% of amaranth flour, whereas Mukhtar *et al*. (2020) reported significantly lower product quality at proportions over 10%. Bread quality also depends on the species of amaranth used; for instance, the addition of 25% and 50% of *A. hypocondriacus* L. flour conferred higher sensory acceptability than *A. spinosus* L. flour. However, amaranth flour should be limited to a maximum of 25% to achieve acceptable sensory and technological qualities (Miranda-Ramos et al., 2019).

Amaranth flour improves the nutritional properties of pasta but reduces its technological characteristics (firmness, cooking loss, and fragility). In general, the proportion of amaranth flour used in pasta production should not exceed 30% (Martinez et al., 2014).

Buckwheat flour is more suitable than other pseudocereal flours for pasta production, having a lower detrimental effect on firmness, cooking time, and cooking loss (Schoenlechner et al., 2010). Some examples are *Pizzocheri*, a traditional pasta from the Valtellina region of Italy, and soba noodles, popular food in Japan, Korea, and China (20–30% buckwheat flour mixed with semolina and 5-30% mixed with wheat flour respectively) (Fongaro & Kvaal, 2013; Puligundla & Lim, 2021).

Bread made with 30% buckwheat flour had higher phenol and flavonoid contents than those made with an equivalent proportion of amaranth or quinoa flour. In addition, technological and sensory properties were improved with the addition of 30% buckwheat flour, even to 100% wheat bread (Chlopicka et al., 2012).

Quinoa, amaranth, and buckwheat flours all improved the quality of GF products, which are typically made with maize or rice flours that have poor sensory, nutritional, and technological properties (Padalino et al., 2016). Buckwheat confers a better sensory quality to bread than quinoa and amaranth and increases Mg, P, K, vitamin E, and phenolic contents (Alvarez-Jubete et al., 2010; Sakac et al., 2011). All three pseudocereals improved the technological properties of GF products. The addition of 50% buckwheat flour and quinoa flour both significantly increased volume, compared to bread made with rice flour and potato starch. In addition, all three pseudocereals confer a softer crumb texture to bread, most likely because of the natural emulsifiers present in the flours (Alvarez-Jubete et al., 2010; Elgeti et al., 2014). Amaranth improves cooking quality and reduces solid loss in GF pasta made with starch and cassava bagasse (Fiorda et al., 2013). The addition of 30% quinoa flour to rice/maize pasta also increased the protein content, particularly when using flour ground from germinated seeds (Demir & Bilgiçli, 2020).

Agronomic limitations to pseudocereal cultivation and distribution

Agronomic analysis and the potential for genetic improvement of pseudocereals lag far behind those of traditional cereal crops**.** Despite their potential benefits, various factors hamper the widespread cultivation and inclusion of these species in modern food systems, ranging from agronomic (growth acreage, yield potential), technological (trait improvement), social (knowledge diffusion), and economic (market buy-in). Nevertheless, an increasing awareness of the opportunity to apply more advanced breeding techniques to improve these underutilised crops is prompting new research initiatives.

Quinoa

Research conducted by the FAO and CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) has established that the largest production of quinoa occurs in Peru and Bolivia, and that production rose 300% from 1980–2011 (Kerssen, 2015). The increasing global demand for quinoa has prompted numerous farmers in African, Asian, European, and North American countries to switch cultivation to this crop. Quinoa species are characterised by high levels of diversity and phenotypic plasticity (Ahmadi et al., 2019) but several crucial points must be addressed if yields are to be improved outside the taxon’s native territory.

Quinoa is highly sensitive to photoperiod. In its native range, flowering and seed filling occur under a short-day photoperiod. This is a limitation that may affect yield and seed quality in areas where days are longer during the growing season, such as northern Europe or southern Chile (Christiansen et al., 2010). Quinoa is also well adapted to the low temperatures of the Andean Altiplano and, as such, is likely less tolerant of the hotter temperatures of many African and Mediterranean countries, which might affect anthesis and early grain filling stages (Matías et al., 2021). These obstacles can be overcome by selecting varieties bred to tolerate adverse environmental conditions. An estimated 6000 varieties of quinoa are currently cultivated around the world, each with distinctive genetic characteristics, which constitutes an exceptional reservoir of genetic diversity exploitable for breeding programs to improve growth and yield (Rojas et al., 2015). Research on regional adaptation includes studies on identifying cultivars capable of growing in southwestern Germany (Präger et al., 2018), evaluation of field performance of five varieties in the Mediterranean Basin (Matías et al., 2021), and determination of flowering times for the development of cultivars adapted to different day lengths (Patiranage et al., 2021). However, unfortunately, not all favourable characteristics have been combined in a single cultivar.

A recent systematic review revealed sowing density and date as the agronomic interventions with the largest influence on quinoa productivity, but these conclusions are based on studies that date back to the 1990s (Sellami et al., 2021). Studies conducted in arid countries like Morocco, Egypt, Burkina Faso, and the United Arab Emirates, along with others at risk of water and salt stress, including Italy, Greece, Turkey, Pakistan, and the United States, have shown that saline water irrigation or salinity stress did not significantly affect the yield and quality of quinoa (Pulvento et al., 2012; Yazar et al., 2015). Therefore, quinoa can be considered a saline-tolerant crop resistant to high salt concentrations in irrigation water.

At lower concentrations, saltwater solutions (25, 50, 75, and 100%) and some salts (NaCl, $CaCl_2$, KCl, and $MgCl_2$) increased the germination speed of quinoa, but not the germination rate.

These treatments affected root and shoot lengths, root morphology, fresh and dry weights, and water content. The salt tolerance of quinoa cultivars can be attributed to a delicate balance between osmotic adjustment and ion accumulation, with differences in ion compartmentalisation between roots and shoots (Panuccio et al., 2014).

A wide diversity of diseases affect quinoa at various growth stages. In the Altiplano, quinoa is affected by downy mildew (*Peronospora variabilis*) at the time of sowing, especially under conditions of high humidity and a temperature range of 15–20°C (Jacobsen, 2017). Infection at early growth stages can compromise the entire harvest, reducing plant photosynthesis and the size of the panicle, and ultimately yield, causing partial or total leaf loss and atrophied plant development. Quinoa is also susceptible to several phytophagous insects belonging to the orders Lepidoptera, Coleoptera, Homoptera, Hemiptera, Thysanoptera, Diptera, and Orthoptera (Gandarillas et al., 2015). In general, the frequency and intensity of pest infestation in quinoa fields depends on geographic location.

Options for controlling diseases vary based on whether conventional or organic production is being practiced. For conventional farming, early applications of fungicides can provide effective disease control; whereas, for organic farming, several different strategies may be employed, including planting more resistant genotypes, early planting, low planting density, and the application of biofungicides, such as plant extracts. For instance, downy mildew has been treated with liquid extracts of horsetail (*Equisetum arvense* L.) and garlic (*Allium sativum* L.), with varying success (Gandarillas et al., 2015).

Amaranth

Amaranthus cruentus L., *A. caudatus* L., and *A. hypochondriacus* L. are the amaranth species that have been domesticated for grain production and commonly referred to as pseudocereals, whereas other amaranth species are consumed as leafy vegetables (Aderibigbe et al., 2020). Although widely used in the food industry, from an agronomic perspective, amaranth has been poorly studied. Grain yields vary widely and are dependent on the site of cultivation and genotype. Plant density is crucial for maximising grain yields, but little data have been published concerning this subject. Gimplinger *et al*. (2008) observed that amaranth produced an optimal yield at a density of more than 50 plants m-2. The primary goals of most amaranth breeding programs are to facilitate mechanical harvesting and reduce seed loss, thus reducing plant height and seed shattering, and improve flowering above the leaf canopy. Other goals include increasing grain yield through the synchronisation of maturity and enhancing grain quality (Joshi et al., 2018).

One challenge relates to the creation of hybrids. Given that amaranth is an autogamous species with a unique flower structure that limits the effectiveness of conventional procedures like hand emasculation and artificial hybridisation, the exploitation of genetic male sterility could be the most efficient way to produce hybrids in these species (Joshi et al., 2018). Indeed several interesting results have been reported from these experiments. Research has also been conducted on examining amaranth performance outside of its native range; for example, Gélinas and Seguin (2008) found that although grain production is possible in eastern Canada, the average grain yield (923 kg ha-1) was lower than that reported in Europe (Gélinas & Seguin, 2008). The primary limitation is the identification of accessions with a location of origin that matches the climate of the target area for production, because many of the amaranth species are sensitive to day length (Wu et al., 2000).

Buckwheat

The cultivation of buckwheat is more widespread than that of quinoa and amaranth. It has been grown for centuries in many countries around the world, both for its grains and leaves. In western countries, however, buckwheat cultivation declined significantly over the 20th century due to increased wheat yield resulting from the Green Revolution (Singh et al., 2020).

Buckwheat has a short harvest cycle and some cultivars are more tolerant to adverse environmental conditions than several traditional crops. Because of these characteristics, buckwheat production aids in sustaining the livelihoods of poor and marginal farmers (Dar et al., 2018). However, buckwheat productivity is low and improvement of seed characteristics, including yield, size, shattering, lodging resistance, and early maturity, are the major objectives of breeding programs for this crop (Morishita et al., 2020). Other targets include the enhancement of seed quality and technological properties, such as easier dehulling, increased groat percentage, removal of allergenic proteins, and increased flour shelf life (Ueno et al., 2016). Tartary buckwheat (*F. tataricum*) seeds, for instance, are intensely bitter due to high levels of rutin, a major reason why buckwheat is not in wider use for human consumption. Several recent reviews discussed the future prospects of buckwheat breeding, with an emphasis on developing cultivars with less bitter-tasting seeds (Suzuki et al., 2021).

Such breeding programs require full examination of the genetic diversity of buckwheat germplasm collections for the identification of appealing agro-morphological characteristics (plant height, number of branches, number of flowers, seed weight, plant type, stem colour, flower colour, seed colour and shape) and for traits associated with seed nutritional value (amino acids, carbohydrates, flavonoids, minerals, phenolics, proteins, and other bioactive compounds) (Chauhan et al., 2010). To date, the overall results suggest high potential for trait improvements. Despite the need to overcome obstacles like apomixis, low seed availability, self/cross incompatibility, a small and complex flower shape, shattering, sterility, and several others. The International Plant Genetic Resources Institute (IPGRI) have initiated programs with the aim of developing higher-quality buckwheat cultivars. Indeed, a considerable number of new buckwheat cultivars with improved characteristics (e.g., seed number, greater genetic stability, low shattering) have already been registered and released in Russia, China, Ukraine, and India (Singh et al., 2020).

Genetics and ‘omics’ resources for breeding programs

Quinoa

Several studies have been carried out to develop molecular markers for identifying and mapping quantitative trait loci (QTLs) and to create new tools for marker-assisted selection (MAS). The first linkage map was developed using single sequence repeats (SSRs), random amplification of polymorphic DNA (RAPD), and amplified fragment length polymorphism (AFLP) markers, covering

60% of the genome (Maughan et al., 2004). Numerous markers have since been identified, including SSR, AFLPs, and single-nucleotide polymorphisms (SNPs) (Maughan et al., 2012). A high-density linkage map of quinoa, consisting of 6403 SNP markers, was recently developed (Jarvis et al., 2017). MAS has enabled the identification of high-yielding early maturing quinoa varieties with low saponin content, as well as greater tolerance to biotic and abiotic stresses (Rodríguez et al., 2020).

Other genomic resources that have been employed include bacterial artificial chromosome (BAC), genomic libraries, and stress-responsive or tissue-specific transcriptome sequencing. BAC libraries were used to identify and characterise the genes that express 11S globulin and 2S albumin seed storage proteins in quinoa, considering an ideal balance of amino acids (Balzotti et al., 2008).

Advanced sequencing technologies and the implementation of bioinformatics software have accelerated genomic and transcriptomic research in quinoa. The use of next-generation sequencing (NGS) platforms has enabled several researchers to independently complete genome sequencing (Yasui et al., 2016; Jarvis et al., 2017; Zou et al., 2017). The results of these activities led to the assembly and annotation of different quinoa accessions and the identification of genes involved in important traits, as reported in a recent review (Rodriguez et al., 2020). In particular, Zou *et al.* (2017), who studied protein quality by comparing lysine, phenylalanine, and isoleucine contents in three protein families of different crops, found that for all three of the protein families lysine content was significantly higher in quinoa than in wheat, rice, and maize. Of the seven enzymes involved in lysine biosynthesis that were identified, the number of gene copies encoding two – diaminopimelate aminotransferase and diaminopimelate epimerase – were higher in quinoa than in the other cereals.

As discussed above, techniques for reducing bitterness in pseudocereals – particularly quinoa – are expensive and can have detrimental environmental impacts. The key genes (*TSARL1* and *TSARL2*) involved in the regulation of saponin production were isolated by sequencing the genome of a Chilean coastal variety of quinoa along with the genomes of other *Chenopodium* species (Jarvis et al., 2017). These genes may be helpful as markers in breeding programs to develop non-bitter varieties of quinoa.

Patiranage *et al*. (2021) observed significant variation in the sequences of the 12 genes involved in flowering time in 276 quinoa accessions. This variability is associated with the geographic origins of the accessions, highlighting the role these genes play in adaptation to differing day-length conditions. The authors further identified five haplotypes that could be assembled in a predictive breeding program to improve adaptation to different photoperiods. Finally, several abiotic stress genes that are similar to those present in cereals have been identified in quinoa; these are involved in ion sequestration, abscisic acid (ABA) homeostasis, and signalling, such as *salt overly sensitive 1* (*SOS1*) (Morales et al., 2017).

Amaranth

Whole-genome sequencing of the amaranth cultivar Plainsman (*A. hypochondriacus*) was completed in recent years, and the sequencing of seven accessions of grain amaranths in phylogenetic studies confirmed that *A. hybridus* L. is the progenitor species of grain amaranths (Clouse et al., 2016). Annotation of the genome of various species of amaranth enabled physical and genetic mapping and identification of the betalain locus. The betalain locus consists of cytochrome P450 (CYP76ADI) and 4,5-DOPA dioxygenase extradiol 1 (DODA1), and is involved in betalain biosynthesis, which in turn regulates stem colouration (Délano-Frier et al., 2011). More recently, the amaranth genome has been used to isolate a set of SSRs, which facilitated the identification of 97 alleles among 10 species of amaranth that could be useful in species determination, DNA fingerprinting, and QTLs/gene(s) detection (Tiwari et al., 2021).

To find genotypes that are adaptable to different environments, morphological, biochemical, and molecular characterisation through the inter-simple sequence repeat (ISSR) of *Amaranthus* varieties was conducted on seven cultivars from India (Rathod et al., 2021). Bioinformatics tools enabled comparative studies on populations of three species (*A. hypochondriacus, A. cruentus,* and *A. caudatus*) and two wild relatives (*A. hybridus* and *A. quitensis*), alongside the *A. hypochondriacus* reference sequence, thereby generating additional insights into the inter-relationships and evolutionary histories of the cultivated species and their wild relatives (Gonçalves-Dias et al., 2021).

However, genetic and genomic research on amaranth lags behind similar work on quinoa and buckwheat. Additional genomic and transcriptomic studies will be necessary to reveal genes and pathways that may be useful for improving amaranth characteristics.

Buckwheat

Several methods were used to unravel the buckwheat genome, including molecular markers, BAC libraries, whole genome sequences, and transcriptomic analysis. Molecular markers, such as RAPDs and SSRs, have been used to study the relationship and estimate the genetic diversity between different accessions of *Fagopyrum* species (Hou et al., 2016). AFLPs were used to identify markers tightly linked to the homostylar region, which determines the homogeneous length of the flower styles (Nagano et al., 2001), and several SSR markers that can be used for MAS and linkage mapping have been developed (Li et al., 2007; Ma et al., 2009). BAC libraries constructed for *F. homotropicum* Ohnishi and *F. esculentum* (Yasui et al., 2008) can also be used for identifying useful genes and formulating molecular markers, while QTLs involved in photosensitivity and stem length have been identified following the genetic mapping of *F. esculentum* and *F. tataricum* (Yabe et al., 2015). Transcriptome analysis facilitated greater understanding of the gene network involved in aluminium toxicity (Chen et al., 2017; Xu et al., 2017), and salt tolerance (Wu et al., 2017), and the identification of the gene networks regulating floral structure (Logacheva et al., 2011). Overall, buckwheat transcriptomics has led to the identification of 11,676 differentially expressed genes in various tissues (Huang et al., 2017). Genomic sequencing has enabled the identification of the genes involved in flavonoid pathways, 2S albumin-type allergens biosynthesis, and granule-bound starch synthase (GBSS). Moreover, the reference genome facilitated identification of the genes involved in aluminium stress tolerance, abiotic stress response, and rutin biosynthesis (Rodriguez et al., 2020). High-throughput sequencing of two buckwheat parents (Tartary buckwheat and rice-Tartary) and two pools from the F2 population was used to identify 633,256 unique SNPs and 270,181 unique insertion-deletion polymorphisms (INDELs). Further, bulked segregant analysis permitted discovery of a genetic region containing 45 SNPs/INDELs and 36 genes that may be involved in seed hull adherence, a finding that may aid breeding programs to identify variants with seeds that are easier to dehull (Zhang et al., 2020).

Socioeconomic and ethical implications of pseudocereal cultivation

Quinoa

Despite extensive research efforts, agronomic techniques for cultivating quinoa are still strictly related to the territory of origin, with practices that are consolidated within indigenous families or small rural communities but are not yet standardised (Ruiz et al., 2014). Therefore, preserving these communities and their agricultural practices is not only of ethical concern, it is also crucial for the diffusion of knowledge to optimise quinoa cultivation both within and outside of the countries of origin. However, conservation of the environment and local communities often conflicts with resource-exploitation interests. The rapid expansion of quinoa cultivation in the Bolivian Altiplano, for example, has increased competition for land with livestock rangelands. In some regions, llama populations have greatly increased because their manure is utilised as a fertiliser, but conversion to quinoa monocultures has significantly reduced fodder availability for llamas that utilise ‘bofedales’, natural wetlands that form an important regional ecosystem (Chelleri et al., 2016). Although growth in the quinoa market has generally raised farmers’ incomes (Bellemare et al., 2018), it has also exacerbated existing social disparities. Farmers who can afford to mechanise their agricultural operations often exploit less wealthy peasants through worker contracts that contain demanding and inflexible terms, promote land dispossession and social conflict (Chelleri et al., 2016). In addition, retailers often reap maximum financial benefits, while farmers remain relatively poor, which, along with climate change, reduces quinoa production (Alandia et al., 2020; Chelleri et al., 2016). In many areas, most notably Bolivia, quinoa yields have begun to decline markedly.

The implementation of regulations that bring tangible benefits to farmers is, therefore, not only an ethical issue but also a tool for optimising quinoa production. In this context, the protection of germplasms and production systems, as well as traditional cultures and practices, is critical. Actions such as the introduction of geographical labels, as was done in Bolivia in 2002, can facilitate conservation efforts (Alandia et al., 2020). Farmer cooperatives have also instituted strict rules for improving the management of natural resources, such as limiting the use of chemicals and the amount of land under cultivation, creating living barriers between fields, balancing grazing and cultivation, and adopting measures that promote crop price stability. Such actions contribute to alleviating pressure on resources and mitigating the negative effects of the upsurge in global demand for quinoa products (Tschopp et al., 2018).

Amaranth

The highest producers of grain amaranth are Mexico, Russia, China, India, Nepal, Argentina, Peru and Kenya, but no official data are published by FAOSTAT about world production (Aderibigbe et al., 2020). The few official data available for amaranth regard India and Mexico; in particular, the leading importer of amaranth from India in fiscal year 2021 was Brazil, with close to 35% ($1 million U.S. dollars) in export value share (www.statista.com). The production of amaranth in Mexico reached six thousand metric tons in 2019. This represents a slight decrease from the output recorded in the previous year. The peak in the production of amaranth in Latin America was registered in 2015, with 9 thousand metric tons. The exports of amaranth from Mexico amounted to $323,000 U.S. dollars. This is the highest figure recorded since the beginning of the indicated period and represents an increase of over 45% in comparison to the value registered in the previous year. Similarly, amaranth imports in Latin America increased, amounting to $339,000 U.S. dollars.

In Africa, amaranth is cultivated by smallholder farmers without a coordinated strategy aimed at developing a market linkage with areas where demand is high, such as European countries.

In Mexico, amaranth represents an important resource for small-scale farmers, who maintain a great diversity within this crop as well as traditional indigenous knowledge about farming. Unfortunately, the supply chain of amaranth is managed primarily by cooperatives, in which associated small-scale farmers have limited roles and incomes. In some cases, small-scale farmers are not allowed to self-commercialise amaranth products, and they are excluded from decisions about processing and trading links. Moreover, the earnings from the sale of the products are not allocated directly to farmers. This system, combined with geographical isolation and difficulties in accessing the internet and processing and marketing information, creates a strong barrier for expanding amaranth production and improving the livelihoods of small-scale amaranth farmers (Bjarklev et al., 2008). To reverse this trend, the Mexican government should protect small farmers, encourage their independent association and include them as real partners and co-owners in cooperatives. In this sense, territorial governance agreements were instituted to promote extensive cooperation among farmer groups, the private sector, researchers, and government agencies to facilitate technology transfer, market strategies and the development of innovative protocols for the control of plant disease, irrigation, harvest and general good practices in the production of amaranth (Martínez-Salvador, 2021).

Buckwheat

Buckwheat is planted worldwide, but Russia and China are the main producers, together reaching 76% of global production (Figure 1). The genus *Fagopyrum* has the greatest diversity in Yunnan Province, situated at the foothills of the Himalaya, where it is considered the “sacred food” for Yi communities. Unfortunately, buckwheat cultivation has significantly decreased since the 1970s because of Chinese government policy that subsidised high-yielding species such as potatoes, maize and bean and maximised monocropping. Other factors responsible for this decline are loss of farm labour due to migration, low incomes for farmers and the accusation of backwardness among traditional species growers (Bulan et al., 2017). However, the increasing commercial success of buckwheat products can reverse this trend, but support from the Chinese government is needed to improve farmers’ incomes and to drive a coordinated development of industry based on this crop.

Genetic breeding of buckwheat is difficult because it is a self-pollinated crop; therefore, seed exchange across different landraces can be the elective mechanism to increase its genetic diversity. To date, the greater diversity of buckwheat is maintained by Tibetan smallholder farmers, but the access of this germplasm is hampered by the harsh geographical conditions and by Chinese policy that focuses on the production of new seed varieties rather than the valorisations of local landraces. To maintain buckwheat diversity, a government change of direction is therefore necessary, one aimed at improving the economic conditions of farmers and the creation of social and technological networks that facilitate the exchange of seeds (Huang et al., 2017).

Conclusions

The nutritional value of pseudocereals and their potential to ensure food security are not discussed here; however, it is noted that their utilisation in the food industry is limited by the presence of compounds that confer undesirable organoleptic and technological characteristics. As such, pseudocereals cannot yet fully substitute for true cereals in bakery products, but at present must be considered solely as supplementary material that can be added to selected food products in small proportions. Although they have great potential for functional foods and to improve the nutritional quality of GF food, it should be noted that the majority of consumers are not gluten-intolerant; indeed, GF foods must be considered as niche products. However, food production is not the only possible way to utilise pseudocereals as the waste derived from technological processes are rich in compounds that are undesirable in food, but may have properties exploitable by cosmetic and nutraceutical producers, in the context of circular economy. The spike in demand for pseudocereals, particularly quinoa, is of major concern for countries within the native ranges of these plants. This is because cultivation elsewhere is often restricted by agronomic and environmental factors that constrain plant growth and productivity, putting more pressure on cultivation in native regions, such as the Andes. The continuing expansion of pseudocereal cultivation represents a grave threat to such biodiverse areas, and may exacerbate socio-economic tensions and conflicts. Cultivation in other countries around the world is therefore urgently needed to ease pressures in the originating countries, which would not only ease the pressure on Andean regions, but also provide opportunities for growers in other nations to diversify their crops. This can be accomplished through the application of strict protocols on the conservation and diffusion of germplasm, land exploitation, and other relevant factors. Moreover, the introduction of geography-based product labelling and regulation of pricing along the entire production chain can help maintain adequate incomes for small-scale farmers. Cooperatives of quinoa farmers are prime examples because they have the capacity to partner with institutions to address issues concerning price regulation and environmental protection; at the same time, however, monopolies must be prevented. Recent dramatic progress in the development of advanced genetic and genomic tools, and analytic procedures, represents an opportunity to disentangle the convoluted diversity of these species to undertake breeding programs for creating cultivars adapted to environmental challenges and with more palatable characteristics. Research efforts remain far from achieving the stated primary objectives; however, limiting the exploitation of these three types of pseudocereals can prevent the depletion of resources and reduce the risk of igniting socio-economics conflicts. Market strategies must take such issues into consideration as, to date, only a handful of human trials assessing the potential beneficial properties of these pseudocereals have been conducted. Industries can utilise these materials in a targeted way to meet actual needs and avoid following trends that are often not based on solid science.

Figure 1. Worldwide distribution of quinoa and buckwheat cultivation. A. Distribution of quinoa cultivation; B. Distribution of buckwheat cultivation. Data were obtained from the official FAO website (http://www.fao.org/faostat/en/#data/QC) for the year 2019.

Declaration of competing interest

The authors declare no conflict of interest for this work

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Figure 1

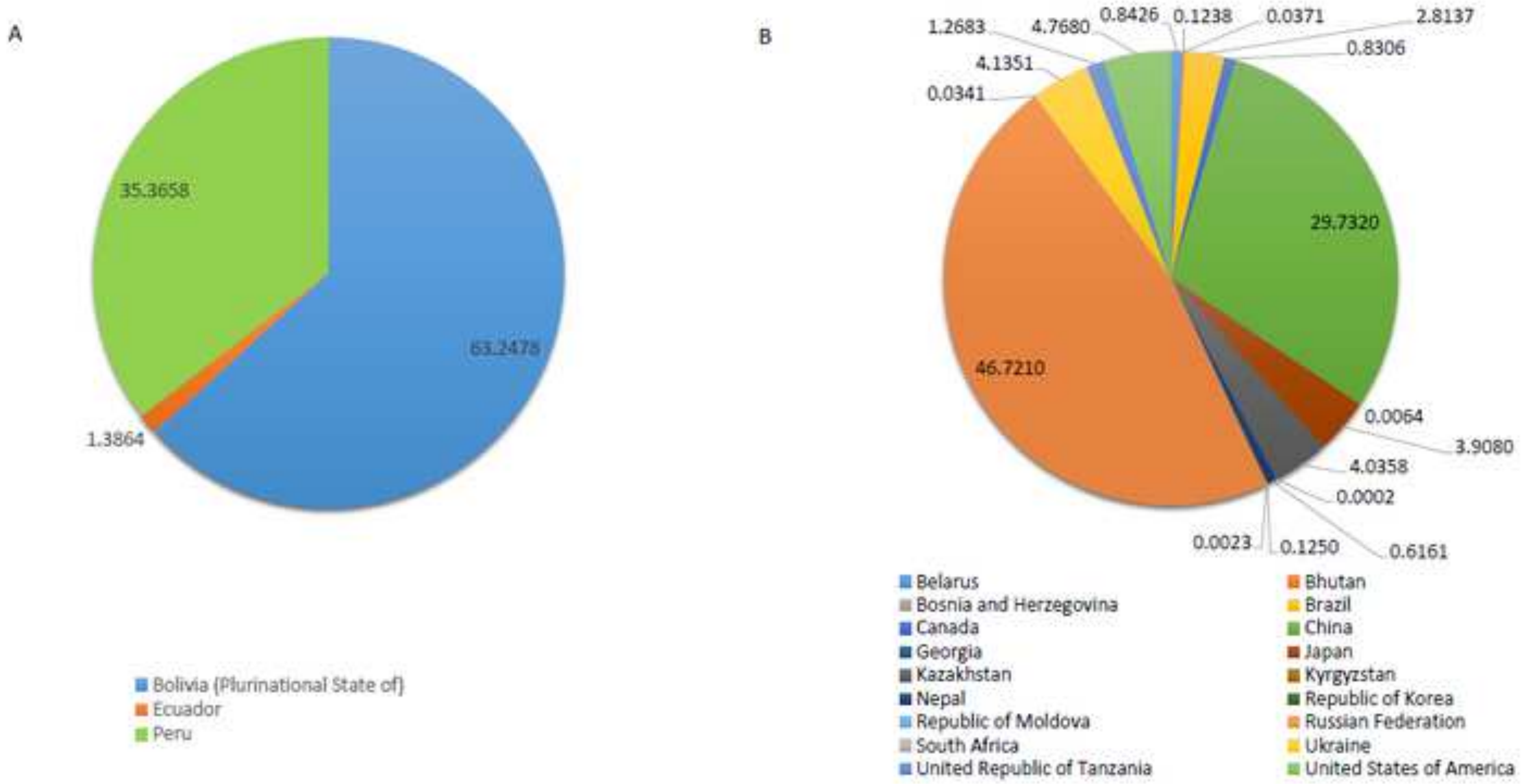
A
35.3658
63.2478
1.3864
Bolivia (Plurinational State of)
Ecuador
Peru
B
1.2683
4.7680
0.8426
0.1238
0.0371
2.8137
0.8306
4.1351
0.0341
29.7320
46.7210
0.0064
3.9080
4.0358
0.0002
0.0023
0.1250
0.6161
Belarus
Bhutan
Bosnia and Herzegovina
Brazil
Canada
China
Georgia
Japan
Kazakhstan
Kyrgyzstan
Nepal
Republic of Korea
Republic of Moldova
Russian Federation
South Africa
Ukraine
United Republic of Tanzania
United States of America

Table 1. Principal nutritional compounds of quinoa, amaranth and buckwheat**.** The amount of starch, proteins, carbohydrates, dietary fibres and phytochemicals measured in flours of quinoa, amaranth and buckwheat are reported together with the main health claims attributed to these pseudocereals.

Species	**Starch** (% of total seed DW)	**Proteins** (% of total seed DW)	**Carbohydrates** (% dry basis)	**Dietary fibres** (% dry basis)	**Phytochemicals**	**Health Claims**
Quinoa (*Chenopodium quinoa*)	1*,2)58.1- 64.2	3*, 4*) 9.1–16.7	3*, 4) 48.5–77.0	3*) 7.0–26.5	5) Ferulic acid 34.85 ± 2.4 µg/g DW 5) Quercetin 23.86 ± 2.5µg/g DW 5) Rutin 21.73 ± 1.8 µg/g DW 5) Vanillic acid 18.80 ± 1.9 µg/g DW 5) Catechin 11.65 ± 0.7 µg/g DW, 5) 3,4-Dihydroxy benzoic acid 8.94 ± 1.2 µg/g DW 5) Gallic acid 6.53 ± 0.9 µg/g DW	6*) hypoglycemic 7*, 8*)antioxidant 9*) anti-inflammatory, antimicrobial, 10*,11*,12*,13*)antiobesity,14*,15*, 16*)antidiabetic, 17*)anticancer, skin protection, immunomodulatory, neuroprotective.
Amaranth (*Amaranth spp.*)	1*,2)65-75	18) 13.1–21.5	1*) 63.1–70.0	18) 2.7–17.3	19) Rutin 1169 ± 215µg CAE/g 19)Feruloylglucaric acid 56.1 ± 0.10 µg CAE/g 19) Caffeoylquinic acid 45.9 ± 9.6 µg CAE/g 19) Hydroxycinnamic acid derivative 38.0 ± 0.8 µg CAE/g 19) Coumaroylglucaric acid 18.6 ± 3.7 µg CAE/g 19) Caffeoylglucaric acid 15.2 ± 2.9 µg CAE/g 19) Quercetin glucoside 66.7 ± 0.17 µg QE/g	20*)anti-inflammatory; antioxidant, blood glucose lowering, 21*) hypocholesterolemic; 22*,23*)antihypertensive, 24*)effect on liver function, anti-anemic, 25*)anti-allergic, regulator of the immune system; 26*) anti-tumor.
Buckwheat (*Fagopyrum esculentum*)	1*, 2)54.5-57.4	27*,28*, 29*) 5.7–14.2	15*)63.1–82.1	9) 17.8	29*) Rutin 4058.13 ± 107.06 µg/g DW 29*) Dihydromyricetin 123.13 ± 12.37 µg/g DW 29*) Kaempferol-3-O-rutinoside 1851.67 ± 54.34 µg/g DW 29*) Quercetin 311.65 ± 3.69 µg/g DW 29*) 4-Hydroxybenzoic acid 274.68 ± 6.53 µg/g DW 29*) Apigenin 180.83 ± 3.57 µg/g DW 29*) Kaempferol 171.22 ± 0.52 µg/g DW 29*) Gallic acid 90.02 ± 4.99 µg/g DW 29*) Syringic acid 66.97 ± 2.43 µg/g DW 29*) 5-Caffeoylquinic acid 38.02 ± 2.49 µg/g DW	30*) hypocholesterolemic, hypoglucemic, hypotensive, anti-inflammatory, neuroprotective, anticancer, anti-oxidant, hepatoprotective, anti-bacterial, anti-fungal, anti-viral, anti-ulcer, anti-fatigue, immunoregulatory, anti-diabetic, cardioprotective, anti-atherosclerosis,, anti-aging, anti-thrombotic

References: 1*) Alonso-Miravalles et al., 2018; 2) Rocchetti et al. 2019; 3*) Nowak et al., 2016; 4*) Pereira et al., 2019; 5) Hemalatha et al., 2016; 6*) Noratto et al., 2019; 7*) Abellán Ruiz et al., 2017; 8*) Graf et al., 2017; 9*) Liu et al., 2018; 10*) Anusha et al., 2018; 11*) Foucault et al., 2011; 12*) Mithila et al., 2015; 13*) Navarro-Perezet et al., 2017; 14*) de Oliveira Lopes et al., 2019; 15*) Li et al., 2018b; 16*) Paśko et al., 2010; 17*) Hu et al., 2021; 18) Joshi et al., 2018; 19) Karama´c et al., 2019; 20*) Tang and Tsao 2017; 21*) Soriano-Santos et al., 2015; 22*) Fritz et al., 2011; 23*) Sabbione et al., 2016; 24*) Olguín-Calderón et al., 2019; 25*) Moranta et al., 2016; 26*) Sultana et al., 2014; 27*) Joshi et al., 2019; 28*) Shukla et al., 2018; 29*)Thanh-Tien et al., 2018; 30*) Huda et al., 2021.

Abbreviations: Dry weight (DW) of flour; Caffeic Acid Equivalents (CAE); Quercetin Equivalents (QE).

*) Reference has been included in the Supplementary Material.

Table 2: Quinoa, amaranth and buckwheat main utilization, antinutritional molecules and their effects, and possible solutions are reported

Pseudocereal	Utilization	Antinutritional Molecules / Effects	Possible solution
Quinoa	1)Bread 1)Pasta 1)Bakery products 4)Sausages 4)Binder for meat burger 4)Salad dressing 4)Cream soups 4)Sauces 4)Pie filling	2)Saponins 2)Bitter taste 2)Reduce Bioavailability of Vitamins	3)Washing 3)Pearling 3)Germination 5)Fermentation
Amaranth	6)Bakery products 6)Bread 4)Binder for meat burger 4)Salad dressing 4)Cream soups 4)Sauces 4)Pie filling 9)Similar cow milk beverage	7)Phytates 7)Chelating property 7)Difficult digestion 7)Reduce bioavailability of minerals	8)Soaking 8)Malting 8)Germination
Buckwheat	10)Pasta 4)Yogurt 4)Vinegar 4)Dark sauce 4)Tea 4)Alcoholic beverage 4)Edible biofilm	11)Hull is non-digestible	11)Dehulling 11)Thermal dehulling

References:1)Filho et al., 2017; 2)Haros and Sanz-Penella, 2017; 3)Suárez-Estrella et al., 2018; 4)Bender et al., 2021
5)Rizzello et al., 2016; 6)Zula et al., 2020; 7)Sanz-Penella et al., 2013; 8)Rollán et al., 2019; 9)Manassero et al., 2020
10)Schoenlechner et al., 2010; 11)Dziedzic et al., 2016.