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Pseudocereals for Global Food Production

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ABSTRACT

Pseudocereals are a group of plants that produce starch-rich seeds that can be used in food applications similarly to cereal grains. The most widely known representatives include buckwheat, amaranth, quinoa, and canihua, which is less well known. All of these pseudocereals have good nutritional compositions, with high concentrations of essential amino acids, essential fatty acids, minerals, and some vitamins. Starch granules in pseudocereals are among the smallest measured, and the starch is characterized by low amylose content (except for buckwheat). The resulting differences in the starch properties of pseudocereals (processing properties similar to waxy-type cereal starches), as well as differences in seed morphology, determine their functional properties. Pseudocereals exhibit high viscosity, water-binding capacity, and swelling capability and good freeze–thaw stability. Additionally, they are gluten-free. Traditional pseudocereal food processes include cooking, popping, roasting, and fermentation, which are used in the production of porridges, soups, stews, and sweet desserts. Products made with pseudocereals do not require large adaptions to processing steps used with cereals. Bakery products and pasta are produced either with flour blends of pseudocereals and cereals, with the main objective to increase the nutritional properties of the final product, or they are made with 100% pseudocereal flour for the gluten-free foods market, which has been one of the main drivers of increased pseudocereal use. Today, breakfast cereals, snack foods, granolas, and cereal-based beverages are the main pseudocereal-based food products sold on the market.

Botanical Description and Seed Morphology

Pseudocereals are a group of plants that produce starch-rich seeds that can be used in food applications similarly to cereal grains. Botanically, however, they are dicotyledonous plants, unlike cereals, which are monocotyledonous plants. The most well-known pseudocereal representatives include buckwheat (*Fagopyrum esculentum* Moench and *F. tartaricum* (L.) Gaertn.), amaranth (*Amaranthus* spp.), and two *Chenopodium* species, quinoa (*C. quinoa* Willd.) and canihua (*C. pallidicaule* Aellen) (Fig. 1).

Buckwheat. Buckwheat is an annual herbaceous plant with many branches that grows to about 60–70 cm in height. The fruit is a triquetrous achene, with a wooden pericarp and one triangular lenticular seed that ripens irregularly (46). The embryo is embedded in the center of the endosperm, which is the main location of the starch in the kernel. The starch granules in the endosperm are round or polygonal depending on their location in the groat. Granules deposited in the peripheral region of the endosperm have a polygonal shape and are tightly packed and embedded in the protein matrix, whereas granules in the central portion of the endosperm are round and loosely packed (30).

Amaranth. The *Amaranthus* genus contains many species, but three species have commonly been grown as food crops: *A. hypochondriacus* L., *A. cruentus* L., and *A. caudatus* L. Grain amaranth is an annual herbaceous plant that can grow to significant heights. The inflorescence, colorful panicles that are amaranthiform, consists of large green, red, brown, orange, purple, or yellow branches; the seeds also vary in color. Amaranth seeds are small, 1–1.5 mm, slightly flattened, and round. The seeds contain the episperm, consisting of a very thin layer of cellular tissue; the endosperm; the embryo, made up of the protein-rich cotyledon; and the starch-rich perisperm (18). Amaranth is known as a short-day plant despite its adaptability to diverse environmental conditions. During planting, a reasonable amount of moisture is essential for germination and flowering, but once established, amaranth is drought tolerant.

Quinoa and Canihua. Quinoa is an annual herbal plant that typically reaches between 0.5 and 1.5 m in height, but it may reach up to 2.5 m in height in some inter-Andean valleys. Flowers are typically arranged in panicles (27). Quinoa seeds measure 1.5–2.5 mm in diameter and are composed of a starchy perisperm, a peripheral embryo, and a one- to two-cell-layered endosperm surrounding the hypocotyl-radicle axis of the embryo. Seed color can vary from white to yellow, purple, brown, or black. Although starch granules occupy the perisperm, the lipid bodies, protein bodies with globoid crystals of phytin, and proplastids with deposits of phytoferritin are the storage components of the endosperm cells and embryo tissues, where phosphor, potassium, and magnesium also are found. The episperm is made up of four layers; the outer layer, which is rough and fragile, contains saponins, which taste bitter. Thus, the outer layer is usually removed prior to processing (discussed in more detail in the Processing Properties of Pseudocereals section) (18).

There are several clear botanical differences between canihua and quinoa seeds, which have been described in detail by Bruno et al. (15). Canihua can adapt well to semi-arid climates at an altitude of 3,600–4,400 m and is not demanding in terms of fertilization and irrigation, but it has a poor yield. Canihua seeds, which are usually brown, are smaller than those of quinoa (~1 mm), which makes harvesting difficult and labor intensive. These challenges, as well as poor yield, may have been primarily responsible for its decreasing use (47).

Pseudocereals, in particular quinoa, canihua, and amaranth, exhibit excellent resistance to drought, frost, salinity, pests, and diseases and can easily adapt to varying environmental conditions. With ongoing climate change predicted, these plants may gain greater worldwide importance in terms of food security.

History of Cultivation and Global Trade Today

Buckwheat. Buckwheat was originally grown in Central Asia and Siberia. From there, it spread to the west, to Turkey, Poland, France, Italy, Switzerland, and Austria, where it is still grown today. In the late 19th century, cultivation expanded to Great Britain, the United States, Canada, Chile, and Brazil. Today, the main producers are Russia and China, which together produce more than 75% of the total buckwheat crop grown worldwide (22). The most commonly grown species of buckwheat is *F. esculentum*. Tartary buckwheat (*F. tartaricum*), also called bitter buckwheat, is only grown and used in very small amounts.

Amaranth. Amaranth was originally grown in the high tropical and subtropical regions of North America around Tehuacán, Puebla, Mexico. *A. cruentus* and *A. hypochondriacus* were grown by the Aztecs in the Valley of Anahuac (Valley of Mexico), while *A. caudatus* was most likely domesticated in South America (Argentina, Peru, and Chile), where it is still cultivated today and is called *kiwicha*, which refers only to *A. caudatus*. For indigenous people in North and South America, amaranth was of high nutritional, cultural, and religious significance, as reported by Spanish explorers. Today, amaranth is grown mainly in Mexico and in South America from Ecuador to Chile in inter-Andean valleys. The main exporters of amaranth are Peru and Bolivia. Amaranth is also grown outside North and South America in Europe, Asia, and Africa (in Africa it is mainly grown as a vegetable), but there is no official data available on production quantities.

Quinoa and Canihua. Quinoa and canihua are two *Chenopodium* spp. that were domesticated in the Andean region of South America by the Inca and Tiwanaku civilizations. Although quinoa is well known today, in large part because of the increasing demand for gluten-free products over the past 10 years, canihua is less well known and is still consumed mainly in its country of origin. Canihua, also known as *cañihua* (Quechua), *kañihua*, *kuimi*, *millmi*, or *cañahua* (Aymara) (15,47), has historically been overlooked because Spanish explorers did not differentiate it from quinoa. It was not until in 1929 that it was designated as a separate species. It was probably domesticated in the Lake Titicaca Basin (23). For pre-Hispanic civilizations, both plants were important staple food sources, and although their production declined after the Spanish conquest, they have remained important sources of protein and, thus, are essential in terms of food security for the region. Today, the main producers are Peru, Bolivia, and Ecuador, but production has expanded to the United States, Canada, Italy, France, England, Sweden, Denmark, and the Netherlands, as well as some countries in Asia and Africa.

Pseudocereals have been niche products for many decades, but about 10 years ago, they began to receive more attention, and consumption, particularly of quinoa, within the Western diet increased dramatically. The main reason for this interest has been the increasing demand for gluten-free products, but trends such as grain-free, wheat-free, ancient, healthy, vegan, and alternative or super foods have been additional drivers. In countries where it has traditionally been cultivated, this growing global demand has caused a shift in quinoa production and trade systems from production as a traditional crop primarily produced for local consumption, to a globally traded commodity, with all its consequences, such as regional supply chains and increases in prices (21). Global trading of pseudocereals requires standardization and specification of raw material quality. To meet these requirements, data on chemical composition, as well as knowledge of applicable analytical methods for pseudocereals, must be available.

Nutritional Properties

Despite similarities in their functional properties, because pseudocereals have different botanical origins, their nutritional composition differs from that of cereal grains. This is particularly true for their protein fractions. Pseudocereals generally possess high nutritional quality. A summary of the nutritional composition of common pseudocereals is provided in Table I.

Carbohydrates. Carbohydrates are the main component in all pseudocereal seeds (60–75%) and are composed primarily of starch. In contrast to cereal grains, in pseudocereals starch is stored in the perisperm. In amaranth, starch granules are among the smallest measured: they are typically 1–3 µm in diameter. In quinoa, starch granules are polygonal or angular, and their size ranges from 0.5 to 3 µm. In addition to single starch granules, compound starch also is found in quinoa, in which several hundred starch granules form aggregates that are 10 to 30 µm (53). In buckwheat, starch granules also have a polygonal shape and are often aggregated. As with amaranth, starch granule size is small (2–14 µm, mean diameter of 6.5 µm) (2). In addition, the amylose content in quinoa and amaranth starches is much lower than in cereal starches, usually less than 10% of total starch. Amylose content in canihua it is slightly higher than in quinoa (11–20%), whereas in buckwheat it is higher than in cereals, with values ranging from 21 to 46% (49,71).

In addition to starch, some mono- and disaccharides are present in pseudocereals. In quinoa and canihua, glucose, fructose, sucrose, and maltose were identified by Repo-Carrasco et al. (53). Low total amounts of mono- and disaccharides in quinoa (6.2 mg/100 g) and canihua (3.1 mg/100 g) have been detected. In amaranth, the mono- and disaccharides detected are sucrose, raffinose, glucose, fructose, stachyose, maltose, and inositol. In total, sugar content varies between 3.08 and 3.29% among 13 amaranth genotypes (4). Buckwheat seems to contain the lowest amount of total sugars (0.4%), but significant amounts of indigestible oligosaccharides have been found, such as fagopyritols (2.6%), which are galactosyl derivatives of D-chiro-inositol that may be useful in the treatment of non–insulin-dependent diabetes mellitus (62). These fagopyritols are localized mainly in the embryo in buckwheat (71.4%) (28).

Protein. Protein in pseudocereals is mainly stored in the endosperm. Although the overall amount is comparable to the amount in cereals, its composition differs significantly. Albumins and globulins are the predominant fractions (together accounting for 60–70% of protein content), while prolamins are found in lower amounts (2–3% in amaranth [6,69]; 3.2–12.3% in quinoa; 28% in canihua [4,17,48,66]; and 0–3% in buckwheat [41,50]). Due to the different distribution of protein fractions compared with cereals, the amino acid profiles of pseudocereals are more advantageous: a high amount of the essential amino acids lysine and methionine is characteristic of cereals, which is often limiting. As a result, pseudocereals have overall high protein quality. For example, with a biological value of 73%, the protein in quinoa is similar to milk casein (4,17,48,66), and for canihua, the protein value is 91–93.3% (23,53). Protein digestibility is usually high for pseudocereals as well. For example, in amaranth digestibility is ~90% (45).

Pseudocereals are considered to be gluten-free. Bergamo et al. (11) examined intestinal T cells from celiac disease patients and transgenic mice and found no immune reactivity after consumption of amaranth. Ballabio et al. (7) also proved that the content of gluten-like proteins was lower than 20 ppm after analysis of 40 amaranth varieties using electrophoresis, immunoblotting methods, and ELISA tests. The suitability of quinoa for inclusion in gluten-free foods was confirmed in a study performed by Zevallos et al. (72). The suitability of canihua has not been yet been measured precisely, but due to its close relationship to quinoa, it is assumed to be gluten-free as well. Nevertheless, this assumption still needs to be proven using analytical measurements. With regard to buckwheat, in food products made with 100% buckwheat flour gluten has been found to be well below the permitted limit for gluten-free products (5). However, buckwheat is a highly potent food allergen that is related to an IgE-mediated, type I immune reaction, causing asthma, allergic rhinitis, urticaria, and angioedema (36). Through processing (e.g., extrusion cooking), allergenic proteins can be partially destroyed (26).

Lipids. Total lipid content in amaranth, quinoa, and canihua is higher than in wheat or rye, whereas in buckwheat content is similar to the ranges for most cereal grains. In pseudocereals, monounsaturated fatty acids are most abundant (~40%), followed by polyunsaturated fatty acids (~30–40%) and saturated fatty acids (~30%) (1,3,60,63). Some pseudocereals contain significant amounts of linolenic acid (e.g., in canihua high amounts of 1.2 to 6.1% have been found) (23,24,53). It is noteworthy that amaranth contains significant amounts of squalene, an intermediate triterpene of cholesterol biosynthesis that exhibits serum cholesterol-reducing activity, and sterols (~20% of the unsaponifiable portion) (12,43).

Dietary Fiber. In pseudocereals the dietary fiber content range is similar to that of cereals or legumes. The major portion of the dietary fiber is insoluble. The soluble portion makes up ~22–34% (3,14,34,35,53). In quinoa, the insoluble dietary fiber is mainly composed of homogalacturonans and rhamnogalacturonan-I with arabinan side chains (~55–60%), highly branched xyloglucan (~30%), and cellulose. In canihua, the amount of dietary fiber is affected by the presence of the outer seed coat (perigonium), which is often removed before consumption. However, the amount of dietary fiber is still high at 12–25%, as determined by Repo-Carrasco et al. (53,55). In amaranth, dietary fiber varies between 8.0 and 20.6% (3,67) depending on the species; in buckwheat, a dietary fiber content of 6.7% has been found (Table I).

Micronutrients. Another outstanding feature of amaranth, quinoa, and canihua is their high micronutrient content. Often their ash content is about twice that of cereal grains. Minerals, in particular copper, iron, magnesium, potassium, calcium, and zinc, occur in high amounts in quinoa, while significant amounts of calcium, zinc, and iron have been found in canihua (55). Amaranth contains high amounts of calcium, iron, magnesium, manganese, potassium, and sodium (3,42). In contrast, buckwheat is not an important source of minerals, although some trace elements, such as selenium, zinc, iron, copper, and nickel, are found in significant amounts in tartary buckwheat (13).

With regard to vitamins, quinoa is a good source of riboflavin (B_2), alpha-carotene, and vitamin C and is an especially good source of folic acid and vitamin E. Folic acid has been found in concentrations of up to 265 µg/100 g, which is 5–10 times higher than concentrations found in wheat (13–51 µg/100 g) (58,61). In amaranth, vitamins such as riboflavin (B_2), niacin (B_3), folate, pyridoxine (B_6), pantothenic acid (3,42,61), and tocopherols (0.73–2.79 mg of total tocopherols/100 g) (64) have been reported. In buckwheat, vitamins such as folate, as well as some other B vitamins, are present in amounts comparable to those found in cereals. Most of these micronutrients are located in the pericarp and embryo, and some of them may be lost during processing, particularly calcium (e.g., in quinoa during abrasion for saponin reduction) (33).

Secondary Plant Metabolites. Phenolic compounds are the most common secondary plant metabolites found in cereals and pseudocereals. Accumulations are often higher in colored seed varieties. In quinoa, colored seed varieties (red or black species) have higher concentrations and antioxidant activities than white quinoa. The major phenolic acids found in quinoa are ferulic acid (76–251.5 mg/kg) and vanillic acid (14–523.92 mg/kg) and their derivatives, whereas the main flavonoids are quercetin (18.41–680 mg/kg), kaempferol (0.25–542 mg/kg), and their glycosides (65). Additionally, phytosterols and betalains, which offer certain health benefits, are present in quinoa. Canihua also seems to be a potential source of natural antioxidants; high concentrations of phenolic compounds (total phenolic content [TPC] of 18.3–40.1 mg/100 g) and flavonoids (46.1–144.3 mg/100 g) have been found (47,51,54). Moreover, the phytate content in canihua seems to be higher than in amaranth but lower than in common cereals (52). Polyphenols in amaranth have been measured at 138.12–286.99 mg of gallic acid/100 g, with rutin being the main compound (30.99–50.78 mg/100 g) (70). Flavonoids (65.0 ± 8.0 mg/g) (16) and betalains (69) also can be found in amaranth. For buckwheat, notable amounts of polyphenols and flavonoids are characteristic—the flavonoids quercetin and rutin, a rhamnoglucoside of the flavonol quercetin, both occur in high amounts and are of special interest. In tartary buckwheat, the occurrence of these flavonoids is sometimes higher (rutin: 810–1,660 mg/100 g; quercitrin: 47–90 mg/100 g) than in common buckwheat (rutin: 10 mg/100 g) and may be responsible for the bitter taste of tartary buckwheat seeds (20).

Saponins. Saponins are bitter-tasting substances that can form complexes with proteins, lipids, and some minerals, such as zinc and iron, and, thus, decrease their bioavailability. On the other hand, depending on the dosage, saponins are anticarcinogenic, antimicrobiological, and anti-inflammatory, decrease cholesterol, and modulate immunity (25,73).

Quinoa contains significant amounts of saponins, ranging from 0.03 to 2.05% (56,57), which are mainly located in the outer layer. Dehulling or washing seeds can decrease the saponin content by up to 72% (57). In contrast to quinoa, canihua contains only very small amounts of saponins, as determined by Rastrelli et al. (51), and the same is true for amaranth (0.04–0.16%) (19,44). As a result, dehulling of these two very tiny seeds is unnecessary.

Processing Properties of Pseudocereals

The main task of processing is to transform raw materials into palatable food products. It is also important to improve digestibility (e.g., starch and proteins) and maintain nutritional properties, while avoiding losses (e.g., minerals, vitamins, TPC). These two tasks must be well balanced. Dehulling and milling to transform whole kernels into flours are often the first processing steps in product development. Although dehulling removes some micronutrients, it can also decrease the content of adverse substances or antinutrients, such as mycotoxins or saponins (in the case of quinoa), which can improve the bioavailability of minerals and proteins.

For each pseudocereal, specific properties must be considered for processing. For example, amaranth, canihua, and quinoa each produce very small seeds, and a relatively large embryo surrounds the starch-rich perisperm. Milling properties are influenced by this seed morphology. For milling buckwheat, it is not seed size, but the triangular form and wooden pericarp that are challenging. Furthermore, all pseudocereals are characterized by small starch granules and very low amylose content (except for buckwheat), resulting in processing properties that are similar to those of waxy-type cereal starches. They exhibit high viscosity, good freeze–thaw stability, higher water-binding capacity, and higher swelling capacity compared with cereal grains. Additionally, all pseudocereals are gluten-free and do not possess any network forming ability. Therefore, processes that require dough-forming properties, such as bread and pasta products, pose challenges and require specific formulation or process adaptations when formulated with pseudocereals alone. Challenges and suggested strategies for food processing with pseudocereals are summarized in Table II.

Historically, common processes have included cooking, popping, roasting, and fermentation of pseudocereals to produce porridges, soups, stews, sweet desserts, or chicha (a type of beer). Today, these processes offer potential applications and adaptations for modern food products. Popping and roasting, for example, increase palatability (producing a pleasant, nutty flavor), while maintaining most of the nutritional properties of the pseudocereal. Breakfast cereals, snack foods, granolas (extrusion cooking, flaking), and beverages are the main products sold on the market today, and they do not require major adaptions of processes used with cereal grains. Bakery products, such as cookies, breads, cakes, or biscuits, and pasta are either produced from flour blends of pseudocereals and cereals (e.g., wheat or maize), with the main objective to increase the nutritional properties of the final product, or they are made from 100% pseudocereal flour for the gluten-free foods market.

Pseudocereals are an ideal option to meet the increased demand for good quality, gluten-free products. This has been one of the main drivers for the increased use of pseudocereals, in particular quinoa, over the past 10 years. Many research studies have been published on gluten-free processing using pseudocereals (3,37,38,59,60), covering a wide range of products, such as breads, biscuits, cookies, cakes, and pasta. Many studies have focused on formulation parameters and examined the effects of ingredients (e.g., hydrocolloids, emulsifiers, enzymes, and plant fibers) used to replace the missing gluten network and improve overall product quality. In a recent project, arabinoxylans were used to form an alternative polymer network in gluten-free buckwheat bread. The authors observed that the arabinoxylan network formed during breadmaking enhanced the rheological properties of the batter (9) and overall bread quality (10), making these polymers suitable for use as natural structure-forming agents in gluten-free breads.

The latest investigations are placing specific emphasis on the modification and adaptation of processing technologies. One example of this is the application of sourdough fermentation in gluten-free bread baking (29,32). With sourdough fermentation, it is important to select the appropriate starter culture for pseudocereals, because the effects of specific lactic acid bacteria on sourdoughs produced with pseudocereals are different than in sourdoughs produced with cereals (32). Additionally, a very recent study has shown that replacing conventional baking technology with ohmic heating could have great potential for overcoming some of the challenges of gluten-free baking. Ohmic heating is an emerging technology in which heat is distributed in a very rapid and uniform manner—heating occurs volumetrically and does not rely on conventional heat transfer based on conduction, convection, or radiation (31,68). Its application in baking gluten-free breads made with buckwheat or millet has demonstrated very promising results (Fig. 2). Texture properties were greatly improved, and evaluation of pasting properties and starch digestibility showed that these breads are comparable or even superior to gluten-free breads baked in a conventional baking oven (8).

In gluten-free pasta processing, starch and its properties have been shown to play a determinant role in product quality (39), and phenomena related to starch retrogradation have been found to play a central role in final product texture (37). Thus, more attention is being paid to the technology used in pasta making, such as utilizing pregelatinized flours or doughs or applying different temperature regimes, to improve gluten-free pasta quality (39,40).

Conclusions

Pseudocereals offer significant nutritional advantages for food products either when blended with cereals or in gluten-free products. Research on food processes utilizing pseudocereal varieties has increased tremendously in recent years, resulting in greater availability of pseudocereal-based food products on the market. This increased utilization of pseudocereals requires a holistic approach on all levels of food production. The continued and engaged efforts of food technologists and industry are necessary to enable the development and production of appealing value-added and gluten-free products. In addition, intensified efforts in all areas of production, trade, and political regulation must be undertaken to ensure that these plants, which are key to food security for many, remain available and affordable for all people.

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Table I. Nutritional composition of the pseudocereals buckwheat, amaranth, quinoa, and canihua

Component (%, dm)	Buckwheat[a]	Amaranth[a]	Quinoa[a]	Canihua[b]
Starch	77.4	58.4	52.2	48.8[c]
Protein	11.5	14.7	12.2	16.1
Fat	2.2	6.3	7.7	8.0
Dietary fiber	6.7	12.7	12.8	12.5
Ash	2.3	2.9	2.7	4.15

[a] R. Schoenlechner and S. Tömösközi (personal measurements, unpublished data, 2014).
[b] Repo-Carrasco-Valencia et al. (53).
[c] Digestible carbohydrates.

Table II. Main challenges and suggested strategies for using pseudocereals in baked products and pasta

Challenges	Proposed Strategies
Seed composition Amaranth, quinoa, canihua • Small seed size • Embryo surrounding the seed • Small starch granule sizes • Low amylose content (processing properties similar to waxy-type cereal starches) Buckwheat • Triangular form and wooden pericarp • Small starch granule sizes • High amylose content	Popping, roasting, fermentation, extrusion cooking • Increase palatability (nutty flavor) • Change physical properties of resulting flours • Maintain nutritional composition Addition of ingredients • Hydrocolloids, emulsifiers, isolated proteins, enzymes, plant fibers, pregelatinized flours (Note: several ingredients are combined) • Arabinoxylan network formation (similar to rye bread) • Pregelatinized flours and doughs (pasta)
Physical properties • High viscosity • Good freeze–thaw stability • Higher water-binding capacity • Higher swelling capability • Protein is gluten-free—No network forming ability	Processing adaptations • Sourdough fermentation (selection of appropriate starter culture) • Application of different baking techniques (e.g., ohmic heating) • Application of different temperature regimes (pasta)
Sensory properties • Different flavor	

Fig. 1. Top (left to right): white, red, and black quinoa; bottom (left to right): canihua, amaranth, and buckwheat.

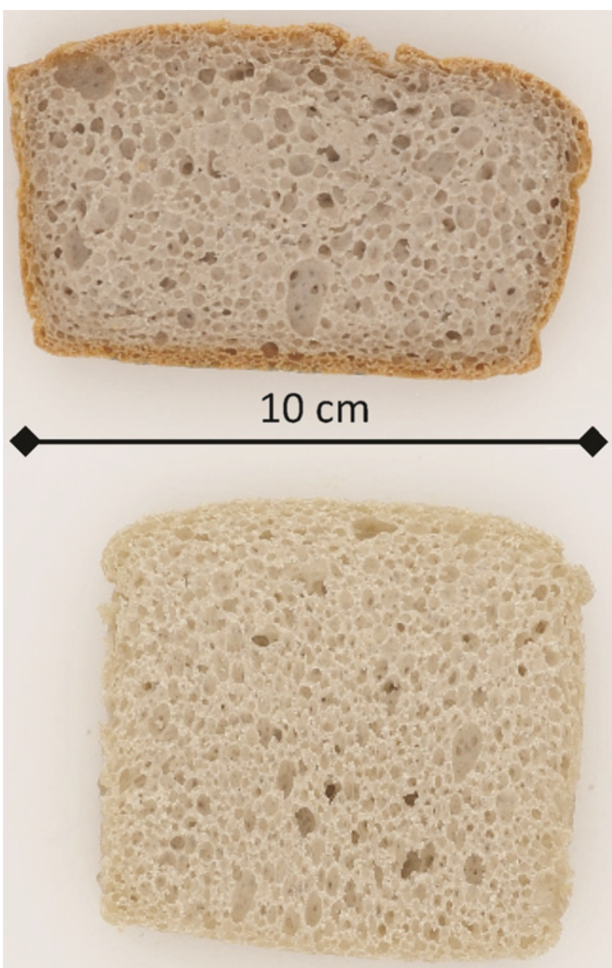

Fig 2. Buckwheat breads baked using a conventional oven (top) versus ohmic heating (bottom).