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**Review**

# Pseudocereals: Development of functional foods, their properties, challenges, and opportunities in food processing industry

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## Abstract

In recent decades, global consumer food preferences have shifted toward healthier and more sustainable options to combat lifestyle diseases. Pseudocereals like amaranth, buckwheat, quinoa, and chia seeds have gained prominence due to their adaptability to different climates and rich nutritional profiles. They provide balanced amino acids, prebiotic starches, fibres, unsaturated fats, B-complex vitamins, vital minerals, and valuable phytochemicals known for their antioxidant, anti-inflammatory, and antihypertensive properties. However, pseudocereals contain antinutritional factors. These can be mitigated through processing techniques such as dehulling, soaking, and thermal treatment, which also influence their physicochemical properties, and enhance their antioxidant capacity. This makes pseudocereals excellent ingredients for functional foods. Historically, pseudocereals were integral to various diets but were super-exploited by processed foods like wheat, rice, and maize in the early 20th century. Presently, there is a growing interest in synbiotic functional foods rich in dietary fibre and fermented by probiotics to support gut health. Fermentation of pseudocereals enhances their probiotic and prebiotic properties, reducing antinutritional factors, and increasing nutrient bioavailability. Pseudocereals are also valued for their high-quality protein content (10 - 20%), often extracted through wet and dry methods, with alkaline extraction for gluten-free, plant-based products. The rise of non-dairy, gluten-free, and plant protein-based products reflects the associated health benefits, including antimicrobial and antioxidant effects. This article reviews the existing literature on potential pseudocereals health benefits, nutritional importance, processing aspects, and scaling up opportunities in the food processing industry.

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## Introduction

Globally, consumers' prescribed selection of foods has drastically changed over the last decades, as they seek clean-label and healthy meals to prevent lifestyle diseases, while demanding that the foods produced be sustainable. Pseudocereals are climate-smart nutri-cereals, due to their high genetic variability that adapt to different resilient climatic conditions, and require fewer inputs for production. The most widely grown and consumed pseudocereals include amaranth, buckwheat, quinoa, and chia seeds, which are rich sources of proteins (with balanced amino acids), prebiotic starches and fibres, fats (unsaturated fatty acids), B-complex vitamins, and minerals, especially calcium, iron, zinc, and magnesium. Additionally, they contain various bioactive substances typically categorised into four groups: phenolic acids, flavonoids (including flavonols, flavones, isoflavones, flavanones, and anthocyanidins), lignans, and stilbenes. Pseudocereals rich in phenolics offer numerous health benefits, including prevention of oxidative stress, cancers, diabetes, cardiovascular diseases, and anti-inflammatory and antihypertensive properties (Kocková *et al*., 2013; Thakur *et al*., 2021).

Pseudocereals, once part of different populations' diets, were super-exploited in the early

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20th century due to their replacement by processed foods like rice, wheat, and maize (Morales *et al*., 2021). Food processing industries are interested in producing synbiotic functional foods. Most commercially available processed foods are poor sources of dietary fibres, which have been associated with higher risk of numerous lifestyle illnesses, including gastrointestinal disorders. Consuming foods rich in fibres is essential as prebiotic components (which are neither digested nor absorbed) are subjected to probiotic bacterial fermentation in the gastrointestinal tract. Probiotics are live lactic acid-producing bacteria that, when used adequately ($10^7$ CFU/g or CFU/mL), ferment the prebiotics, modulate the gut microbiota, and confer benefits upon host health. Synbiotic functional foods containing prebiotics and probiotics are considered for a healthy gut, which promotes the overall health of people (Poshadri *et al*., 2022). There is a vast demand for plant-based non-dairy foods, gluten-free products, plant-based meat alternatives, and plant protein-based foods. This rapid change in food habits might be due to health benefits associated with plant-based probiotics, prebiotics, and synbiotic functional foods (Ugural and Akyol, 2022).

Cereals like corn, wheat, and rice comprise roughly 80% of food consumption, and are biofortified to enhance vitamins and other essential micronutrients. On the other hand, pseudocereals are inherently enriched with these crucial micronutrients, but have yet to be investigated for large-scale production and consumption. The Food and Agriculture Organization (FAO) has identified many plants as underutilised, which can significantly improve nutrition and health, enhance food baskets and livelihoods, and ensure future food security and sustainable development. These underutilised crops offer immense potential in the functional food sector to combat hidden hunger crises, and offer income-generation options (Boye *et al*., 2012).

Moreover, underutilised crops are closely tied to cultural traditions, and therefore envisaged to support social diversity. An increasing interest in research and development needs heightened direction and focus on exploring these neglected or lost crops. This review article examines the existing literature on potential pseudocereals' health benefits, nutritional importance, processing aspects, and scaling up opportunities in the food processing industry.

### *Pseudocereals*

Pseudocereals are dicotyledons, and their physicochemical properties are more consistent with cereals. Pseudocereals of whole grains and their proteins can be used to formulate bakery and confectionery products, replace animal proteins, prepare meat analogues, and texturise vegetable proteins, baby foods, and breakfast cereals (Figure 1). Many pseudocereals are cultivated globally, such as album, amaranth, buckwheat, chia, quinoa, and wattle seeds (Malik and Singh, 2022).

Album (*Chenopodium album* L.), also known as bathua, belongs to the family Amaranthaceae. Album seed contains protein (15 - 17%), fat (6 - 7%), carbohydrate (48 - 50%), and ash (5 - 6%). The grains are mostly ground into flour, or sprouted to produce malt. It can be used to substitute or partially replace wheat to produce nutritionally rich bakery products such as breads, muffins, cakes, cookies, and biscuits in China and Russia (Fletcher, 2016).

Amaranth (*Amaranthus cruentus* L.) was a major staple food after rice and wheat for pre-Colombian people, and has now become an important ingredient in functional extruded snacks and other gluten-free foods. It belongs to the family Amaranthaceae. Along with useful bio-actives, it also contains protein (14 - 17%), fat (1.5 - 3%), carbohydrate (60 - 62%), fibre (8 - 9%), and many other vitamins and minerals (Deshpande and Poshadri, 2011). Composite flour most commonly contains amaranth flour as an ingredient for manufacturing nutrient-dense fortified foods including bakery products such as breads, cakes, cookies, malted foods, pastas, crackers, and other functional foods.

Buckwheat belongs to the family Polygonaceae. Common buckwheat (*Fagopyrum esculentum* Moench) and Tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertn) are the most cultivated and consumed pseudocereals in the world. It contains protein (10 - 13%), fat (1.4 - 4%), carbohydrate (59 - 70%), fibre (3 - 4%), minerals (magnesium, potassium, and phosphorus), and vitamins ($B_1$, $B_2$, and $B_6$). Buckwheat also contains more amylose than other pseudocereals, and is a source of resistant starch (27 - 33.5%). Higher-resistant starch modifies blood glucose and lipid profiles, reduces obesity, and regulates gut flora (Huda *et al*., 2021; Yalcin, 2021).

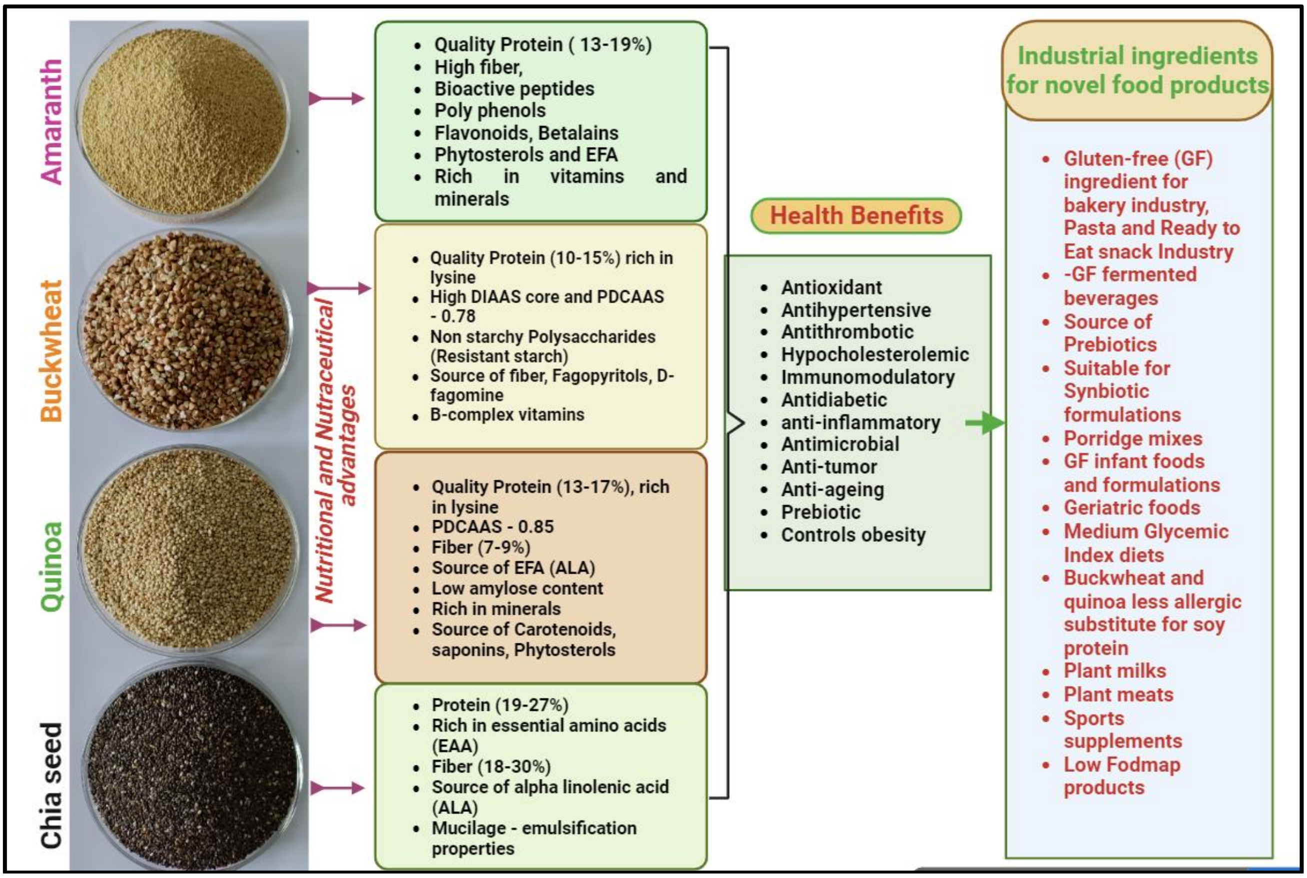

**Figure 1.** Nutritional and functional advantages of pseudocereal as industrial ingredients for food processing industry.

Quinoa (*Chenopodium quinoa* subsp. quinoa) is a rich reservoir of carbohydrate (64%), protein (14%), fat (7%), and other nutrients, and belongs to the family Amaranthaceae. Quinoa protein is a good source of amino acids such as histidine and lysine. It does not contain gluten, and is suitable for people diagnosed with celiac disease (Ayub *et al*., 2021). Compared to amaranth and buckwheat, it has a lower amylose level. Quinoa’s bioactive peptides can be utilised as innovative ingredients for developing different kinds of nutraceuticals or functional foods that can be used to treat a range of lifestyle disorders (Demir and Bilgiçli, 2021).

Chia seed (*Salvia hispanica* L.) is a fat-rich pseudocereal, a good source of linolenic acid (59.9 - 63.2%), and belongs to the family Lamiaceae. It is consumed as whole grains or flour with refreshing drinks. Chia seeds' gelling and fat-binding properties can be utilised to create functional foods rich in proteins, fibres, minerals, and bio-actives (Khalid *et al*., 2023).

Wattle seed (*Acacia saligna* (Labill.) H.L.Wendl.) is a gluten-free seed belonging to the family Fabaceae. It contains protein (23 - 32%), fat (14 - 19%), carbohydrate (32 - 36%), fibre (33 - 41%), and minerals (3.4 - 3.9%). Wattle seeds have higher proportion of antinutritional factors. Soaking grains overnight, followed by boiling and roasting seeds, reduces them (Ee and Yates, 2013; Shelat *et al*., 2019).

Globally, the usage of pseudocereals is increased due to the health benefits associated with the consumption of amaranth, quinoa, and buckwheat, and problems associated with meat products, such as chronic diseases, colon cancer, environmental problems, carbon emissions, animal welfare ethics, water use, and land impact. Dietary fibre in pseudocereals is a non-starch polysaccharide. Regular consumption of pseudocereals lowers the risk of chronic diseases, such as certain types of cancer, diabetes, obesity, and hypertension. Zhu (2020) and Yang *et al*. (2021) reported that the supplementation of amaranth reduced the levels of triglycerides, total cholesterols, and phospholipids in the mice's liver. Furthermore, globally, food diets have drastically changed over the last decades due to technological advances in the food processing industry, consumer awareness of food composition, and convenience in food preparation. The changes suggest reconsidering super-exploited foods like pseudocereal-based products to ensure the health and well-being of consumers.

However, pseudocereals also contain antinutritional factors that may inhibit the absorption of nutrients. Amaranth contains certain antinutrients such as saponins (0.9 - 4.91 mg/kg), phytic acid (2.9 g - 7.9 g/kg), tannins, lectins, alkaloids, and protease inhibitors (Jan *et al*., 2023). Quinoa contains antinutritional components such as saponins (6.27 - 692.49 mg/kg), phytic acid (10.5 - 13.5 g/kg), tannins, oxalates, nitrates, and trypsin inhibitors found in the outer layers of the grain (Thakur *et al*., 2021). Trypsin inhibitors, endogenous antinutritional factors found in buckwheat, restrict protein bioavailability and absorption (Sofi *et al*., 2023). The processing techniques can be used to reduce antinutritional factors from legumes, cereals, and other foods. The processing techniques include dehulling, pearling, soaking, thermal treatment, germination, fermentation, irradiation, ultrafiltration, and enzymatic treatments. Table 1 reviews various processing technologies for pseudocereals, demonstrating their nutritional and functional health benefits, and potential for formulating gluten-free products.

*Pseudocereals proteins*

The protein quality of pseudocereals is higher than that of cereals and legumes, present in 10 - 20%, and is suitable for the isolation of proteins and their hydrolysates. Albumin and globulin make up the majority of pseudocereal proteins, in contrast to cereal proteins (Deleu *et al*., 2019). In general, proteins can be extracted using dry and wet processing methods. Alkaline/isoelectric precipitation, acid extraction, water extraction, and micellisation are examples of wet processing techniques. Electrostatic separation and air classification are examples of dry processing techniques. Alkaline extraction is the most frequently utilised method of protein isolation (Figure 2). Plant protein solubility is higher at alkaline conditions, and co-precipitation of non-protein components is significantly less at alkaline conditions. Alkaline extraction of plant proteins can also be used to isolate the proteins from pseudocereals to replace wheat, meat, and dairy proteins, and develop gluten-free products, non-dairy flavoured milk, and plant-based meat analogues (Penchalaraju and John Don Bosco, 2022).

*Probiotic and prebiotic properties of pseudocereals*

Food's probiotic ability is influenced by several elements including $a_w$, pH, salt, sugar, food additive, food processing temperature, moisture content, packaging, storage condition, and composition. Foods high in probiotics are trustworthy, non-toxic, devoid of pathogens, and able to adhere to intestinal cells. The probiotic properties of amaranth have been observed. *Lactobacillus rhamnosus* bacterium was added to amaranth flour, which was then blended with water or milk, caramel, and chocolate flavours. After two weeks of storage, there was no discernible change in the mixture's nutritional makeup, and lactic acid bacteria (LAB) strains were present in amounts between $10^8$ and $10^9$ CFU/mL (Matejčeková *et al*., 2016). Based on research investigations, the probiotic activity level for the product up until its shelf life should be between $10^6$ and $10^7$ CFU/mL. The bioavailability of vitamins, minerals, bioactive substances, the quality and digestibility of proteins, and antibacterial action to control the growth of unwanted microorganisms are all improved by fermentation. The probiotic and other symbiotic functions of fermented foods made with the addition of pseudocereals can be utilised to treat colon cancer, irritable bowel syndrome, gastrointestinal issues, and constipation (Miranda-Ramos and Haros, 2020). Ugural and Akyol (2022) reported that pseudocereals can be used in formulating synbiotic foods through natural fermentation or using probiotic cultures, to induce the synthesis of short-chain fatty acids, and reduce the load of pathogenic microorganisms (Ruminococcaceae, Lachnospiraceae, Helicobacteraceae, *Clostridium*, and *E. coli*) due to their prebiotic effects. Further, amaranth proteins can be used as a potential source of antidiabetic and antihypertensive peptides for functional food formulation (Kamal *et al*., 2021).

Fermentation of quinoa exhibited probiotic and prebiotic properties, reduced antinutritional factors, and increased the bioavailability of vitamins. 30% of quinoa mixed with other ingredients gives the best results in nutritional components, antimicrobial activity, antibiotic activity, and antioxidants. Fermented quinoa showed the highest growth rate of *Lactobacillus* species ($10^9$ CFU/mL) during 28 days of storage with fructooligosaccharides as a prebiotic,

**Table 1.** Studies which reported the development of different foods using pseudocereals.

| Pseudocereal | Description | Result | Reference |
|---|---|---|---|
| Amaranth | Dry roasting and excess jet-cooking of amaranth flours for making high protein, gluten-free noodles. | The study assessed the compositional and physicochemical properties of raw, roasted, and jet-cooked amaranth flours and their influence on noodle quality. Raw amaranth flour was high in lysine, glycine, histidine, and crude protein contents. Raw amaranth flour had darker colour, higher water-holding capacity, higher peak viscosity, softer noodle dough, and noodles with a more soothing bite than wheat flour. Roasting improved the cooking yield and texture of cooked noodles. Roasted amaranth flour showed potential to supersede wheat flour in the development of acceptable gluten-free, nutritive noodles. | Singh and Liu (2021) |
| Amaranth and buckwheat | Amaranth was used as a base for the vegan diet pasta, and different proportions of buckwheat flour (15, 30, and 50%) were added. | The study revealed that a combination of buckwheat and amaranth produced a highly nutritious pasta. | Beltane and Marisheva (2023) |
| Buckwheat | Whole buckwheat was used for the preparation of pasta products. Buckwheat was used for couscous product. | Pasta prepared with whole buckwheat had higher total phenol content (1090.0 ± 22.4) and couscous (1062.7 ± 8.7) compared to cereal and legume-based products. The cereal products' phenolic and dietary fibre compounds can alter according to the cereal species and the flour's extraction rate. Interestingly, pasta and couscous from particular legumes and pseudocereals can have higher protein, fibre, and polyphenol contents than cereal products (even whole meal cereal products), and higher range of notes of gluten-free cereal products. | Carcea *et al*. (2017) |
| Buckwheat | Good source of bioflavonoid rutin, resistant starch, lysine, proline, flavones, flavonoids, phytosterols, D-chiro-inositol, and myo-inositol. | Flavonoid compounds in buckwheat are essential to improving human health, preventing and healing different diseases. However, the safety and toxicity profiles of buckwheat's roots, leaves, and hulls have not been wholly analysed until now. | Huda *et al*. (2021) |
| Buckwheat and chia flour | Gluten-free premix with buckwheat and chia flour in a 90:10 ratio to produce bread. | The premix and bread prepared with the addition of buckwheat and chia flours exhibited the highest protein, ash, crude fibre, antioxidant, and polyunsaturated fatty acid. | Coronel *et al*. (2021) |

| | | | |
|---|---|---|---|
| Quinoa | The effect of pearling on the physicochemical properties, bioactive compound contents, and antioxidant capacity of quinoa flour. | Whole and pearled flour from three quinoa varieties showed variations in physicochemical properties, bioactive compound contents, and antioxidant capacity. The pearling process can effectively remove the saponin content in quinoa seeds, and it showed better antioxidant activity and functional properties. These results may provide a basis for the utilisation of quinoa flour in various applications. | Jiang *et al*. (2021) |
| Quinoa | The extruded quinoa snack was coated with spores of *Bacillus coagulans* suspension composed of salt and oil at 70°C, and its probiotic viability was assessed during coating, storage, and *in-vitro* gastric passage. | The viability remained after coating and storage above $10^7$ CFU/g, and showed 70% survival in the gastric passage, suppressed pathogenic bacteria, and qualified as a probiotic quinoa snack. | Muñoz Pabon *et al*. (2022) |
| Corn, broad bean, and quinoa | The gluten-free pasta spaghetti was prepared with corn flour, 30% broad bean, and 20% quinoa flour to improve the nutritional quality of the pasta. | The nutritionally enriched gluten-free pasta-spaghetti product significantly increased net protein utilisation, decreased true digestibility, and improved mineral composition. The addition of composite flours had a synergetic effect on protein quality. | Giménez *et al*. (2016) |
| Quinoa and chia seeds | The study compared the nutritional and textural properties of gluten-free pasta made from quinoa and chia seeds with durum wheat pasta. | The gluten-free pasta made from 85% quinoa and 15% chia seed flour demonstrated superior cooking, nutritional, functional, and sensory properties. | Khatri *et al*. (2023) |
| Chia seeds | Wheat bread was enhanced with higher nutrient levels by replacing wheat flour with raw chia seeds and chia flour, and defatted chia flour at 5 and 10% levels. | Wheat bread with chia seed or flour contained higher protein, fat, mineral, fibre, linoleic acid, and lower glycaemic index compared to 100% wheat bread. | Miranda-Ramos and Haros (2020) |
| Composite pseudocereal flours | A composite blend of gluten-free pseudocereal flour was prepared in three different blending ratios, and assessed for their functional properties to explore as an alternative ingredient for wheat flour. | The functional properties of the composite flour blend, which contained amaranth, buckwheat, and quinoa in proportions of 50, 40, and 10%, respectively, were found to be superior. This could be an effective replacement for wheat-based products when trying to improve the structural and textural qualities of gluten-free foods, which are primarily affected by the presence of gluten. | Poshadri *et al*. (2023) |

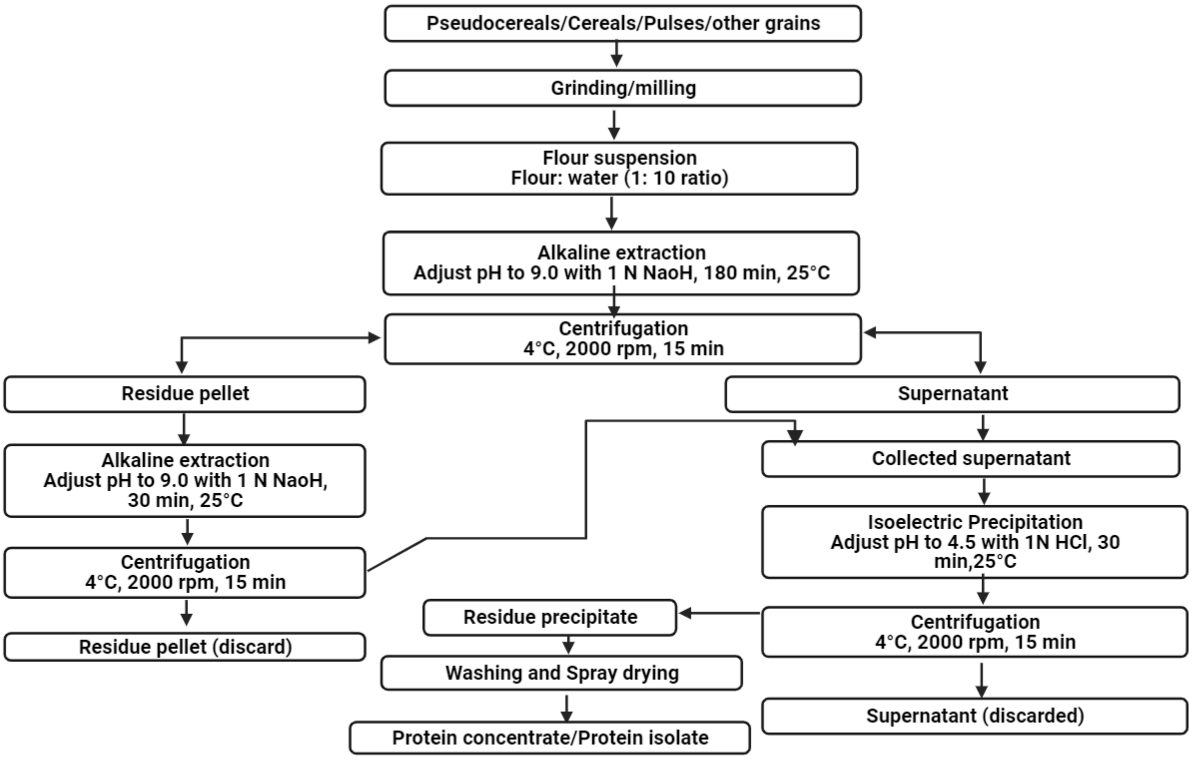

**Figure 2.** Isolation of plant proteins using alkaline/isoelectric precipitation method.

probiotic, and synbiotic effect (Franco *et al*., 2020). Coda *et al*. (2010) observed higher levels of free amino acids, γ-amino butyric acid (GABA), phenolic compounds, and antioxidant activity in sourdough bread made from a blend of amaranth, buckwheat, quinoa, and chickpea flour than wheat flour bread. Rocchetti *et al*. (2019) discovered enhanced total phenolic compounds and oxygen radical absorption capacity in buckwheat and quinoa after boiling or toasting, followed by fermentation with LAB strains.

### *Processing of pseudocereals*

Pearling operations significantly affected quinoa flour's physicochemical properties, bioactive components, and antioxidant capacity. The water solubility index, swelling power, water absorption, and fat absorption capacity decreased considerably in pearled compared to whole quinoa flour. The phenolic, flavonol, and saponin contents of quinoa flour decreased considerably after pearling treatment. The saponins and antioxidant capacity of quinoa flour also decreased considerably (Jiang *et al*., 2021).

Roasting and steam jet cooking significantly affected the physicochemical properties of amaranth flour, such as bulk density, hydration capacity, cooking time, dough hardness, and cooking losses to prepare gluten-free noodles. Roasted amaranth flour has the potential to replace wheat flour in the preparation of acceptable gluten-free, nutritive noodles (Singh and Liu, 2021). Buckwheat is noted for its total cholesterol reduction properties, neuroprotection, anticancer, anti-inflammatory, antidiabetic, antioxidant, and prebiotic properties. These buckwheat properties are due to bioactive compounds, such as D-chiro-inositol (DCI), proteins, and flavonoids (rutin and quercetin) (Giménez-Bastida and Zieliński, 2015). Germination can be used to reduce the antinutritional factors in cereal flour. A study conducted has shown that 37% of the protein increased, and 77% of phytic acid decreased due to the germination process of cereals used for pasta production (Demir and Bilgiçli, 2021). The addition of pseudocereals can increase the physicochemical properties of the final product. Quinoa and germinated quinoa flour can increase the mineral content and colour characteristics L* and a* values.

Buckwheat can be used to produce dough with viscoelastic properties. The viscoelastic property of dough is the most desirable for developing bakery products such as breads and biscuits. Buckwheat flour positively impacted insoluble fibre, crumb cell circularity, and loaf-specific volume. It is a nutraceutical functional food that may be used to make noodles, breads, and biscuits, and can replace rice and potato in recipes (Southgate *et al*., 2017). In diabetic mice, buckwheat's soluble dietary fibre has hypolipidaemic and hypoglycaemic effects. Due to its ability to boost glucose levels, lipid metabolism, and the production of short-chain fatty acids, Tartary buckwheat has antidiabetic properties (Wu *et al.*, 2021). Pseudocereals with high amylose concentration can delay digestion, and have excellent stability with digestive enzymes.

### *Synergetic effect of pseudocereals on intestinal microbiota*

The most popular pseudocereals include quinoa, chia, buckwheat, and amaranth. These grains have been consumed as healthy foods since they are devoid of gluten, packed with nutrients, and contain higher amounts of bioactive compounds than regular cereals. A possible explanation for the synergistic effects of pseudocereals and their by-products is the presence of residual lactic acid fermentation, which results in the formation of enzymes, bioactive substances, exopolysaccharides, bioactive substances with health-promoting properties, antimicrobial agents, alcohols, and organic acids (Aguilar *et al.*, 2019; Ugural and Akyol, 2022). Pseudocereals have historically only been used in a few food preparations, but now that advanced processing technologies are available, they can be used as either ready-made or composite ingredients to create novel functional foods like gluten-free bakery goods, extruded ready-to-eat snacks, breakfast cereals, energy drinks, or other synbiotic functional beverages and cold extruded products like noodle, pasta, and vermicelli. The pseudocereals' synergistic benefits may be attributed to proteins, polyphenols, rutin, and quercetin (Giménez-Bastida and Zieliński, 2015).

## Conclusion

The evolving global dietary preferences and growing concerns about health and sustainability have led to a resurgence of interest in pseudocereals, including amaranth, buckwheat, quinoa, wattle seeds, album, and chia seeds. These pseudocereals are gaining recognition for their remarkable nutritional profiles and potential health benefits. They are rich in proteins, prebiotic starches and fibres, unsaturated fatty acids, B-complex vitamins, and essential minerals. Additionally, they contain various bioactive compounds, such as phenolic compounds, flavonoids, lignans, and stilbenes, which have been linked to health benefits, including the prevention of oxidative stress, cancers, diabetes, and cardiovascular diseases. These pseudocereals have a pivotal part in addressing the evolving dietary landscape. As consumers increasingly seek clean-label, healthy, and sustainable foods, pseudocereals offer a valuable alternative as they can be used in a wide range of food products, from bakery items to meat alternatives, developing nutritious and functional foods. Despite their advantages, pseudocereals pose challenges due to antinutritional factors that impair nutrient absorption. However, processing techniques can address these issues, making pseudocereals more accessible and appealing to a broader audience. In conclusion, the resurgence of pseudocereals in modern food production aligns with the evolving global food landscape. These resilient and nutritious grains have the potential to play a crucial role in meeting the demands for healthier, sustainable, and functional food products. Their unique properties make them a valuable addition to the quest for improved public health and sustainable nutrition. Further research and development are essential to unlocking the full potential of pseudocereals, and expanding their presence in the contemporary food market.

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