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Application of emerging non-thermal pre-germination technologies to optimise the germination of Andean pseudocereals and their use in gluten-free baked products

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Abstract

This review examines three Andean pseudocereals: quinoa (*Chenopodium quinoa* Willd.), kañiwa (*Chenopodium pallidicaule* Aellen), and kiwicha (*Amaranthus caudatus* L.). The focus is on the changes achieved through germination, enhanced by the use of emerging technologies applied as a pre-treatment. These grains are characterized by high-quality proteins with a complete essential amino acid profile, significant dietary fiber content, and diverse bioactive compounds with antioxidant, antihypertensive, and antidiabetic properties. This review covers conventional germination methods and parameters and explores emerging non-thermal technologies used as a pre-germination step. Although substantial research has investigated these technologies in quinoa, studies on kañiwa and kiwicha remain limited. Current evidence indicates that technologies such as ultrasound, high hydrostatic pressure, cold plasma, and magnetic fields can optimize enzymatic activity, reduce antinutrient content, and promote the synthesis of functional compounds. Gluten-free baked products made from germinated flour demonstrate improvements in rheological, textural, and sensory properties. However, challenges persist in defining industrial-scale parameters and addressing the high manufacturing costs of gluten-free products. A bibliometric analysis shows an increasing global interest in gluten-free products, creating commercial opportunities for these Andean pseudocereals. Kañiwa is identified as particularly promising due to its climatic resilience and nutritional value. The conclusion emphasizes the need for further research to optimize processing protocols and validate scaling approaches, thereby enhancing the contribution of pseudocereals to global food security and sustainable development.

Keywords Quinoa, Kañiwa, Kiwicha, Germination, Non-thermal treatments, Gluten-free, Bioactive compounds

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1 Introduction

Andean pseudocereals, such as quinoa (*Chenopodium quinoa* Willd.), kañiwa (*Chenopodium pallidicaule* Aellen), and kiwicha (*Amaranthus caudatus* L.), have gained relevance due to their high content of proteins, essential and non-essential amino acids, dietary fiber, and bioactive compounds [1]. These grains contain peptides with antioxidant and antihypertensive potential, as well as flavonoids and other phenolic compounds with anti-hyperglycemic activity that can help control elevated blood sugar levels, preventing type 2 diabetes, cardiovascular, and gastrointestinal disorders [2, 3]. Recent research also suggests potential anticancer activities attributed to these phytochemicals, sparking growing interest in healthy food and nutraceuticals [4–6].

Among these, quinoa is the most widely recognized. Its remarkable adaptability to adverse agroecological conditions, including low-fertility soils, water stress, and high salinity, has favored its expansion from the Andean region to Europe, Asia, and Africa [4, 7]. Kañiwa exhibits similar or greater resilience to extreme climates and poor soils at high altitudes, yet its cultivation remains local and its genetic diversity underexploited [6, 8]. Kiwicha, valued for its drought and heat tolerance, has also not achieved global distribution despite its health benefits, including cardiovascular protection and glycemic regulation [9, 10].

The rising prevalence of gluten-related disorders has intensified the demand for nutritious gluten-free alternatives, a need that Andean pseudocereals are particularly well positioned to address [11–13]. However, formulating high-quality gluten-free baked goods remains technologically challenging due to the absence of gluten's viscoelastic network–a limitation that germinated Andean grains can help overcome by contributing both structural functionality and nutritional enhancement [14–16]. Germination is a sustainable and economical biotechnology that activates endogenous enzymes, reducing antinutrients, increasing protein digestibility and mineral bioavailability, and promoting the synthesis of bioactive compounds including GABA, phenolics, and flavonoids [14, 17–20].

More recently, emerging non-thermal technologies applied as pre-germination treatments have gained attention. Ultrasound, high hydrostatic pressure, cold plasma, and magnetic fields can prime seeds by enhancing water uptake, stimulating enzymatic activity, and decontaminating seed surfaces, leading to faster, more synchronous, and biofortified sprouting [21, 22]. Despite promising results in quinoa, studies on kañiwa and kiwicha remain scarce, and generalisation from quinoa is not straightforward due to differences in seed structure and composition. Moreover, industrial scalability, cost, regulatory, and sensory considerations are insufficiently addressed.

Therefore, this review aims to: (i) analyze the nutritional and functional composition of Andean pseudocereals, (ii) synthesize the fundamentals and critical parameters of germination, (iii) evaluate the application of emerging non-thermal technologies to germination, (iv) review the use of germinated grains in gluten-free baked products, and (v) identify current challenges and future research priorities. By addressing these objectives, this work highlights the potential of these strategies to optimize the biological activity and functional properties of these grains for innovative food applications. It contributes to SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), and SDG 12 (Responsible Consumption and Production) by promoting the sustainable use of resilient, nutrient-dense native crops.

2 Methodology

This narrative review was conducted using a search strategy in specialized databases such as Scopus, ScienceDirect, SciELO, Web of Science, and Google Scholar, considering literature published between 2015 and July 2025. The following keywords were used: germination, Andean grains, quinoa, amaranth, kiwicha, and kañiwa, combined with terms related to food applications and bioactive components, including food applications, bioactive compounds, protein, fiber, amino acids, antioxidants, bakery products, and gluten-free. The inclusion criteria were limited to original research articles and review articles available in full-text and in the press until July 2025. To ensure relevance, studies were selected based on their focus on nutritional, technological, or functional aspects of germinated Andean pseudocereals. Other grains, such as buckwheat, were also included for comparative purposes. To provide a broader perspective, bibliometric insights were incorporated to enrich the discussion.

3 Andean pseudocereals: composition and functional potential

Andean pseudocereals are globally recognized for their gluten-free profile and high nutritional density [15]. Scientific evidence attributes relevant physiological activities to the bioactive compounds present in these three grains, including antioxidant, antimicrobial, and anti-inflammatory capacities, suggesting a potential role in health promotion and disease prevention [23].

3.1 Quinoa

Quinoa (*Chenopodium quinoa* Willd.) is a globally recognized Andean pseudocereal valued for its nutritional composition and health-beneficial properties [24]. The FAO considers quinoa a "superfood" or "golden grain" [25]. As a gluten-free grain, it is a good option for people with celiac disease or gluten intolerance [24]. Its protein content (approximately 15 % dry matter) substantially exceeds that of conventional cereals, with globulins and albumins constituting up to 70 % of total proteins, a favorable distribution compared to the prolamin-dominant profiles of wheat and corn [4, 24–26].

Quinoa contains 17 amino acids, including all essential amino acids, with particularly notable amounts of lysine 2 to 3-fold higher than wheat, compensating for the primary amino acid deficiency in cereal-based diets [4]. The dietary fiber content is higher than most cereals and comparable to fruits, with a predominance of insoluble over soluble fractions [25]. Regarding bioactive compounds, quinoa contains flavonoids, such as quercetin, rutin, and kaempferol derivatives, as well as γ-aminobutyric acid (GABA) [26, 27]. Total phenolic content varies dramatically by variety: black and red ecotypes contain substantially higher phenolics than white varieties, highlighting the importance of genotype selection for functional food applications [26]. Quinoa also stands out for its high mineral content, particularly potassium, magnesium, and iron, which substantially exceed those of cereals like wheat and corn, though concentrations vary among varieties and growing conditions [25, 28]. Germination can further increase iron bioavailability through phytate degradation [28].

However, the nutritional value of quinoa is partially limited by antinutrients, particularly saponins (which impart bitterness) and phytic acid, that reduce mineral bioavailability and require removal through processing, such as washing, germination, or thermal treatment [25, 28]. This intraspecific variability in both beneficial compounds

and antinutrients suggests that process optimization must be coupled with careful variety selection.

Detailed numerical ranges for all parameters discussed above, including protein, amino acids, fiber, bioactive compounds, minerals, and antinutrients, are presented in Table 1 and Supplementary Table S1.

3.2 Kañiwa

Kañiwa (*Chenopodium pallidicaule* Aellen) is an ancestral Andean pseudocereal native to the highlands of Peru and Bolivia, used by pre-Columbian cultures for centuries and fundamental in Inca nutrition alongside corn and potato [2]. Considered an ancestral nutraceutical and functional food with great industrial potential [6], it stands out as a strategic pseudocereal for sustainability [29, 30]. Its notable genetic diversity is evidenced by the morphological variability of its ecotypes in Puno (*Chilliwa*, *Purple plant*) and traditional classifications by habit (*Lasta*, *Saiwa*) and color (*Wila*, *Qillu*) [29]. It is characterized by resistance to adverse climatic conditions, including low temperatures, strong winds, frost, and prolonged droughts without yield reduction, positioning it as an ideal crop for food security facing climate change [3, 6].

Kañiwa is an important protein source, with a protein content that surpasses that of many conventional cereals. Varieties such as *Ramis* and *Cupi-Sayhua* reach high protein levels, with an optimal balance of essential amino acids comparable to milk casein [6]. It is rich in lysine, often a limiting amino acid in plant-based foods, as well as isoleucine, threonine, methionine, and histidine [2, 6]. Other important amino acids present include alanine, serine, and proline [16]. Compared to quinoa, kañiwa has similar levels of key amino acids such as lysine, leucine, and tryptophan [31]. The main protein fractions identified in kañiwa are albumins and globulins [3]. The absence of gluten makes it suitable for consumption by people with celiac disease or gluten sensitivity [2]. Its dietary fiber content is significant [3]. Regarding mineral composition, kañiwa provides notable amounts of potassium, phosphorus, calcium, iron, magnesium, zinc, manganese, and copper [6].

It contains various phenolic compounds and flavonoids associated with antioxidant and anti-inflammatory activities [2]. Total phenolic compound levels vary among Peruvian kañiwa ecotypes, with higher levels reported in varieties such as *INIA 406-ILLPA* and *Cupi* [2, 29]. Germination has been shown to substantially increase γ-aminobutyric acid (GABA) content and reduce phytic acid, improving the nutritional profile and mineral bioavailability [32]. Kañiwa contains three types of triterpenoid saponins. A notable characteristic is that kañiwa saponins lack the bitter taste found in quinoa [6].

Detailed numerical ranges for all parameters discussed above are presented in Table 1 and Supplementary Table S1.

3.3 Kiwicha

Kiwicha (*Amaranthus caudatus* L.) is an Andean pseudocereal recognized for its high nutritional value and functional properties [33]. It is an important protein source with a balanced amino acid profile, including notable amounts of lysine, an essential amino acid often limiting in cereal-based diets [5, 6]. Its seeds constitute a source of nutritionally dense compounds, distinguished by their balanced protein content, complete amino acid profile, substantial concentrations of β-carotene, vitamins, essential minerals,

Table 1 Chemical composition, nutritional profile and antinutrients of Andean pseudocereals: quinoa, Kañiwa and kiwicha

Grain	Proximate Composition (%)	Protein fraction	Amino acids	Antinutr.	Minerals (mg/100 g)	Bioactive compounds	Ref.
Quinoa (*Chenopodium quinoa Willd.*)	P: 13.5–17 L: 3.95-–8.7 C: 64.6-–77.0 F: 3.5–10	11 S albumins (35%), 2 S albumins (35%), prolamins (0.5-–7.0%)	Essential and sulfur amino acids, lysine, methionine, histidine, isoleucine or cysteine	0.01–5% Saponins Quinoline Phytic acid	Ca^{2+}: 54–87 Mg^{2+}: 26–502 Fe^{3+}: 1.4-–16.8	Phenolic compounds: 27–58 mg GAE/100 g. Carotenoids, trans-lutein (84.7-–85.6%) and zeaxanthin. Contains all four tocopherol homologs (α-,β-,δ- andγ-tocopherols),γ-tocopherol most abundant	[16, 23, 28]
Kañiwa *(Chenopodium pallidicaule Aellen)*	P: 15–19 L: 6–7 C: 45–63 F: 5.8–18	Albumins 16–41%, globulins 26%, prolamins 10–28%, glutelins 23–31%	Lysine, tryptophan, methionine and threonine	Non-bitter saponin	Ca^{2+}: 60–141 Mg^{2+}: 33–167 Fe^{3+}: 4–15	Total phenolic compounds: 57.9-–85.71 mg GAE/100 g. Catechin, gallate, vanillic acid, kaempferol, ferulic acid, quercetin, resorcinol and 4-methylresorcinol. Carotene 2.0 mg/100 g. Flavonoids: 11.4 μmol catechin equivalents/g. Antioxidant capacity (hydrophilic phase): 1509.80 μg Trolox/g	[3, 7, 23, 31]
Kiwicha *(Amaranthus caudatus L.)*	P: 12-–14.5 L: 5.7-–8.3 C: 29–63 F: 4.4–11	Glutelins (24.9-–29.9%) Albumins (39%) Globulins (19.9%) Prolamins (2–3%)	Leucine, phenylalanine and lysine	Phytic acid	Ca^{2+}: up to 306 Mg^{2+}: 338 Fe^{3+}: 7.3	Total phenolic compounds: 15.5-–17.4 mg gallic acid/100 g	[29, 33, 34]

Scientific names: Quinoa (*Chenopodium quinoa Willd.*), Kañiwa (*Chenopodium pallidicaule Aellen*), Kiwicha (*Amaranthus caudatus L.*). Abbreviations: P (Protein), L (Lipids), C (Carbohydrates), F (Fiber), GAE (Gallic Acid Equivalents). Mineral values converted to mg/100 g for consistency

antioxidant and anti-inflammatory properties, and the absence of gluten [5, 34]. The dietary fiber content of kiwicha is significant and composed mostly of insoluble fiber [20]. Regarding mineral composition, kiwicha provides notable amounts of iron, zinc, and manganese, though concentrations vary among ecotypes and growing conditions [33, 35]. The germination process can further increase the bioavailability and content of these minerals.

Total phenolic content varies among varieties, with glutamic acid being the most abundant amino acid in raw and malted kiwicha [35, 36]. Lysine contents are notably high, compensating for limitations in cereal-based diets [5]. As with other Andean grains, the nutritional value of kiwicha is partially limited by antinutrients, particularly phytic acid, that require reduction through processing, such as germination [19].

Detailed numerical ranges for all parameters discussed above are presented in Table 1 and Supplementary Table S1.

4 Germination process and its benefits

Germination is a biotechnological process and a traditional, economical, and efficient method that significantly improves the nutritional and functional profile of Andean pseudocereals, such as quinoa, kañiwa, and kiwicha [37]. As shown in Fig. 1, this process involves the management of parameters (time and temperature), following a series of events that begin with water absorption by the dry seed and end with the elongation of the embryonic axis [38]. Enzymatic pathways are activated, degrading reserve compounds that give rise to the synthesis of new proteins and secondary metabolites. The seed-to-water ratio typically ranges from 1:5 to 1:4, and the time can vary. For example, in some studies, quinoa is soaked for 6, 12, or even 16 h [18, 19, 39, 40]. The optimal temperature varies according to the study objective but is commonly between 20°C and 25°C. Relative humidity is maintained high, generally between 85 and 100 %. Germination is often conducted in darkness to favor the increase in compounds such as GABA [19, 40].

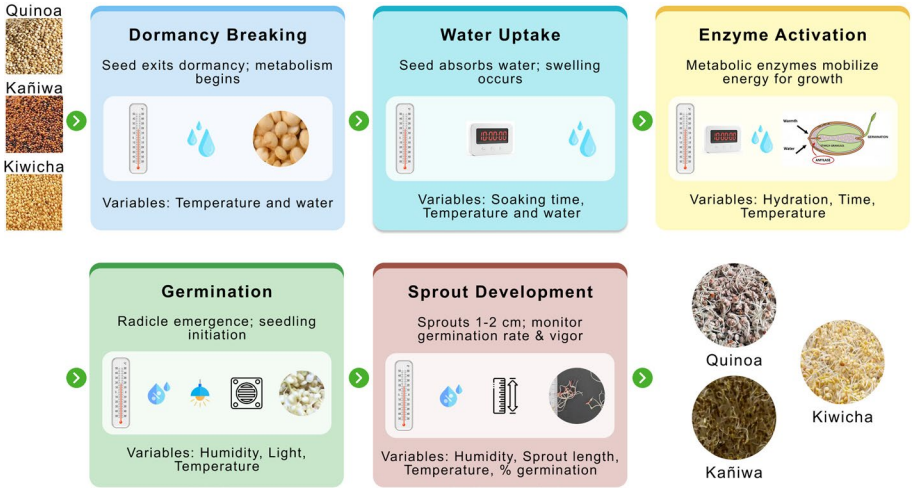


Fig. 1 Schematic diagram of the controlled germination process for quinoa, kañiwa, and kiwicha. The diagram illustrates the sequential physiological stages from dormancy breaking to sprout development, along with the key controlled variables (time, temperature, humidity, light) that modulate enzymatic activation, antinutrient degradation, and bioactive compound accumulation

Therefore, the germination of Andean pseudocereals allows for the improvement of their nutritional and functional profile, decreasing antinutritional factors (phytic acid, tannins, and saponins) and increasing digestibility, as well as the sensory qualities of the germinated sprouts [14, 20, 41–43]. Thus, this process optimizes the nutritional profile through increased protein digestibility, micronutrient bioavailability, and possible biosynthesis of bioactive compounds through secondary metabolic pathways. Simultaneously, it modulates techno-functional properties (viscosity and texture) and organoleptic attributes in derived food matrices, resulting in sensory improvements for their advantageous applications in the food industry [15].

Various clinical and epidemiological investigations suggest that including these germinated whole grains in the diet could provide significant health benefits [39]. They represent a potential source of bioactive peptides with different pharmacological activities, such as antimicrobial, antioxidant, antihypertensive, and antidiabetic properties [6]. Daily intake of quinoa, kañiwa, and kiwicha reduces cardiometabolic risks [23].

Consequently, the emergence of different methods to control grain germination has aroused growing interest in enhancing nutrients as effective strategies to improve nutritional and antioxidant properties [21, 39].

4.1 Effect of traditional germination conditions

Traditional germination practices primarily include soaking, time regulation, and temperature control. These factors directly influence the biochemical changes of grains, impacting their functional properties and final food quality. These methods are detailed below.

4.1.1 Soaking

For better germination results, soaking is an important step [21, 35, 39]. The goal is to hydrate the grains to break dormancy and activate the endogenous enzymatic system. Soaking it causes significant changes [21], such as the loss of nutrients like globulins (the main protein in quinoa). It is also considered an effective process for removing antinutrients such as saponins, phytic acid, and tannins [38]. The decrease in protein content is temporary and begins to increase as germination progresses, partly due to the loss of dry matter (carbohydrates and lipids) [19, 38]. A similar effect occurs with minerals, involving an initial loss through leaching. This is followed by a relative increase in their concentration and a significant increase in the bioavailability of key minerals such as iron, zinc, and calcium. The relative gain results from the loss of dry matter, whereas the improved bioavailability is largely due to the reduction of phytic acid, which releases the trapped minerals [19, 38].

Soaking also directly reduces grain hardness and activates the endogenous enzymatic system [21, 44]. Furthermore, combining soaking with germination increases the concentration of crude protein in pseudocereals, with the extent of the increase depending on the duration of the treatment [35]. In the case of kañiwa, soaking can promote an increase in proteins up to 19.11 %, phenolic compounds up to 386.12 mg GAE/100 g, and antioxidant activity up to 114.92 μmol TE/g dry weight [45]. An increase in fiber is also observed, depending on the soaking time, from 4.19 % to 4.33 % [40]. In kiwicha, the combined process of soaking and germination can produce significant changes in fiber content due to the synthesis of new cell wall components and the degradation of other

macronutrients [35]. Table 2 comparatively shows the changes produced by the effect of soaking time on the nutritional composition and antinutrient content of quinoa, kañiwa, and kiwicha.

In summary, soaking is the initial hydration phase that activates the seed's enzymatic machinery, breaking dormancy, and initiating the metabolic cascade that will intensify during the subsequent germination period [19, 21]. While soaking alone triggers measurable changes, such as the early stages of protein hydrolysis and the diffusion of water-soluble antinutrients like saponins, its primary function is to prepare the seed for the complex biosynthetic and degradative processes that occur during radicle emergence [38, 44]. The significant accumulation of bioactive compounds, such as GABA and polyphenols, and the maximization of mineral bioavailability are achieved during germination proper; soaking merely enables these later, more pronounced improvements [21, 35].

4.1.2 Germination time and temperature

The optimization of time and temperature in the germination of quinoa, kañiwa, and kiwicha is crucial for maximizing bioactive compounds and minimizing antinutrients

Table 2 Effect of soaking time on the nutritional properties, bioactive compounds, and antinutrients of Andean pseudocereals

Grain	Treatment	Nutritional	Bioactive compounds	Antinutrients	Ref.
Quinoa	Soaking (0, 12, 24 h) 1:5 (w/v) - 25°C	Fiber: 5.56, 5.80, 6.59%. Protein: 14.94, 15.45, 15.74%. Carbs: 60.12, 59.58, 59.09%. Minerals (mg/kg): Cu^{2+} 6.55, 7.08, 7.73. Fe^{3+} 107.17, 108.10, 134.82. Zn^{2+} 69.82, 73.15, 79.98. Mn^{2+} 14.30, 14.58, 15.23	Antioxidant (DPPH): 46.41, 48.02, 50.99%. TPC: 48.07, 54.45, 56.59 mg GAE/100 g	Tannins: 0.048, 0.042, 0.041%. Phytic acid: 1.03, 1.01, 0.97%	[35]
Quinoa	Soaking 30 min Germination 72 h at 25°C	Fiber: — Protein: 12.56%. Starch: reduced to 53%	TPC: increased 6–8%. Antioxidant: increased 2%	Phytic acid: 10.41 to 9.39 mg/g. Tannins: 0.40 to 0.21 mg CE/g	[39]
Quinoa	Soaking 2 h 1:4 (w/v) at 25°C	Fiber: 4.19 to 4.33%. Protein: 19.91 to 21.08%. Carbs: 71.56 to 70.44%	Flavonoids: 10.87 to 14.86 mg QE/100 g. TPC: 52.88 to 58.32 mg GAE/100 g. Antioxidant: DPPH: 48.33 to 52.63%. FRAP: 9.23 μmol TE/g. ABTS: 14.44 μmol TE/g	—	[40]
Kañiwa	Soaking 7 h 1:5 (w/v) at 23°C	Fiber: 6.88%. Protein: 19.11%. GABA: 100 mg/100 g	TPC: 386.12 mg GAE/100 g. Antioxidant (ORAC): 114.92 μmol TE/g	Phytic acid: 0.88 g/100 g	[32]
Kiwicha	Soaking (0, 12, 24 h) 1:5 (w/v) - 25°C	Fiber: 3.83, 3.89, 3.93%. Protein: 17.80, 17.63, 17.86%. Carbs: 60.79, 60.64, 61.61%. Minerals (mg/kg): Cu^{2+} 8.88, 9.02, 9.50. Fe^{3+} 127.92, 132.92, 135.25. Zn^{2+} 30.50, 31.70, 32.87. Mn^{2+} 31.67, 32.05, 32.87	Antioxidant (DPPH): 18.75, 19.47, 20.77%. TPC: 32.68, 45.67, 53.00 mg GAE/100 g	Tannins: 0.065, 0.059, 0.056%. Phytic acid: 1.15, 1.13, 1.10%	[35]

Scientific names: Quinoa (*Chenopodium quinoa Willd.*), Kañiwa (*Chenopodium pallidicaule Aellen*), Kiwicha (*Amaranthus caudatus L.*). Abbreviations: TPC (Total Phenolic Content), GABA (γ-aminobutyric acid), DPPH (2,2-diphenyl-1-picrylhydrazyl), GAE (Gallic Acid Equivalents), QE (Quercetin Equivalents)

(phytic acid, tannins, and saponins). Once the seed has been hydrated, temperature and duration govern the extent of metabolic transformations during the germination period.

In quinoa, at 25 °C for 72 h, enzymatic pathways are activated, increasing proteins from 13.5 to 14.13 % [19, 46], antioxidants to 241 μmol TE/g, and reducing saponins by 58–85 % and phytic acid by 63–79 %, albeit with losses in minerals (K^{2+}, Mg^{2+}, Zn^{2+}) and tocopherols (17.5 %) [47]. However, moderate temperatures appear most effective. One study determined that the optimal temperature to maximize TPC and antioxidant activity was 20 °C for 42 h, showing increases of 80 and 30 % in TPC and antioxidant capacity, respectively [18]. In other varieties, peaks were observed between 48 and 72 h, although prolonged germination can lead to polyphenol loss [46]. The GABA content in quinoa increased more than five-fold after 63 h of germination at 26 °C. Another study found a GABA peak at 60 h [18].

Germination time is crucial for antinutrient reduction. The phytic acid content in quinoa decreases with increasing germination time, by 59–64 % after 96 h and up to 74 % after 7 days [19, 39]. Similarly, a 27 % after 72 h [35]. Beyond 72 h, respiratory losses reduce dry matter [44, 48]. Furthermore, genetic variability (black and red quinoa varieties present higher antioxidant levels compared to white ones) [47, 49] and the lack of standardization in humidity and light conditions demand differentiated protocols, where temperatures above 28 °C stimulate vitamin degradation, while times exceeding 72 h activate saponin synthesis [49–51]. Therefore, the time-temperature-variety balance is essential for industrial applications to avoid sacrificing functional quality.

In kañiwa grains, to maximize total soluble phenolic compounds (386.12 mg GAE/100 g dry weight) and antioxidant capacity (ORAC: 114.92 μmol TE/g dry weight), the optimal germination conditions were 20 °C for 72 h [32]. In kiwicha, germination at 26 °C for 63 h increased the GABA content 29-fold, phenolic compounds reached 869–926 mg GAE/100 g after 48 to 72 h of germination, and antioxidant capacity reached 202–450 μmol TE/100 g [52]. Similarly, another study reported a 126.62 % increase in the phenolic content of amaranth after 72 h of germination, where the black-grained ecotype showed higher phenol levels than the pink one [35]. There was also a significant reduction of 32.30 and 29.57 % in the contents of tannins and phytic acid, respectively, after 72 h of germination [35]. In a similar vein, the concentration of nearly all essential amino acids was found to increase, except methionine, tryptophan, and valine [53]. For kiwicha grains, germination times between 48 and 72 h at temperatures around 20–25 °C were the most effective for improving the nutritional and functional profile [52].

Table 3 summarizes the germination parameters and their nutritional effects on Andean pseudocereals, while detailed data can be found in Supplementary Material Table S1.

Germination time and temperature are critical factors that increase the functional and nutritional attributes of Andean pseudocereals. The optimization of time and temperature during germination is important to maximize protein, antioxidant, and mineral content while simultaneously controlling conditions to prevent undesirable degradation.

5 Innovations: germination assisted by emerging (non-thermal) technologies

Non-thermal treatments for Andean pseudocereal germination include techniques such as ultrasound, high hydrostatic pressure, cold plasma, and magnetic fields, which stimulate enzymatic activation and seed permeability without causing damage. These methods

Table 3 Effect of germination on the nutritional composition, bioactive compounds, and antinutrients of Andean pseudocereals

Grain	Varieties	Germination parameters	Nutritional changes	Bioactive compounds	Antinutrients	Ref.
Quinoa	Blanca, Roja, Negra, Amarilla, Gris, INIA Salcedo, Pasankalla, Negra Collana, Marangani, Lord of Orchard, Chaucha, Tunkahuan, Pata de Venado	24-72 h at 20-28°C RH 70-95%	Protein: +5-123% Fiber: +9-18% Vitamin C: +32-50% Minerals: Fe^{3+} +15-39%, Ca^{2+} +25-49%, Zn^{2+} +10-45% Reducing sugars: +41-566% Essential AA increased	TPC: +17-179% Flavonoids: +28-39% Antioxidants: DPPH, FRAP, ABTS, ORAC increased GABA: +6-33% Phenolic acids increased	Phytic acid: -22-79% Saponins: -45-60% Tannins: -11-31% Phytase: +64-149%	[18, 19, 35, 37, 38, 42, 43, 46, 48–51, 54–56]
Kañiwa	Illpa	72 h at 23°C RH≥90%	Protein: slight reduction Nutritional quality improved	GABA: +795% TPC: +23% ORAC: +135%	Phytic acid: -25%	[32]
Kiwicha	Black, Pink, various ecotypes	24–78 h at 23-35°C RH 55–100%	Protein: +8-18% Carbohydrates: +11% Fiber: +75% Protein digestibility: +0.88-9% Essential AA increased Minerals increased	TPC: +35-306% GABA: +2810% ORAC: +542% Antioxidants: DPPH +35-450% Betalains increased Bioactive peptides	Trypsin inhibitors: eliminated Lectins: -71–95% Saponins: eliminated Phytic acid: -30%	[20, 35, 36, 52, 57–59]

Scientific names: Quinoa (*Chenopodium quinoa Willd.*), Kañiwa (*Chenopodium pallidicaule Aellen*), Kiwicha (*Amaranthus caudatus L.*). Abbreviations: TPC (Total Phenolic Content), GABA (γ-aminobutyric acid), AA (Amino Acids), DPPH (2,2-diphenyl-1-picrylhydrazyl), FRAP (Ferric Reducing Antioxidant Power), ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), ORAC (Oxygen Radical Absorbance Capacity), RH (Relative Humidity)

accelerate and optimize the germination process. A summary of their effects on nutritional composition is presented in Table 4, while a more detailed version is available in Supplementary Table S2. Detailed descriptions of each technology are provided in the following subsections.

5.1 Ultrasound

Ultrasound waves are a type of sound wave with a frequency of 20 kHz to 1 MHz, inaudible to humans [65]. It is an emerging, non-thermal, ecological, and low-energy consumption technology applied before or during germination to activate the biosynthesis of nutraceuticals and improve the nutritional profile of seeds [60]. Its application involves high intensity at different frequencies, typically from 28 to 40 kHz [39, 40].

5.1.1 Principle and optimization strategies

Waves are categorized based on their power density into low energy (< 1 W/cm^2) and high energy (10–1000 W/cm^2) [66]. Their biophysical effects critically depend on the applied power, frequency, and exposure time. Studies have applied frequencies from 28 to 40 kHz for durations, such as 30 min [39, 40], or high power (100 W) for short periods (4 min) [61]. Treatment conditions are often combined with specific post-treatment drying temperatures (50 °C or 60 °C) to optimize the response [40, 60].

5.1.2 Mechanisms and effects on germination biochemistry

Ultrasound-assisted germination constitutes an advanced strategy that induces significant biochemical shifts to enhance the nutritional and functional profile of quinoa seeds (*Chenopodium quinoa* Willd.) [40, 60]. The primary mechanisms and their consequences are:

- Micro-cavitation and Cell Wall Permeability: The acoustic cavitation generated by ultrasound induces microcavitation, acting as a stress elicitor that increases membrane permeability and intracellular mass transfer [67]. This accelerates seed hydration, provides enzyme access to substrates, and facilitates the release of elements retained in the matrix, thereby enhancing mineral availability [60].
- Enzyme Activation and Metabolism Regulation: The treatment modulates metabolic activity and stimulates the activation of key germination-associated enzymes [67]. This regulates metabolism, promotes the biosynthesis and release of bioactive compounds, and facilitates the degradation of reserve macromolecules. A major consequence is the significant reduction of antinutritional factors, such as phytic acid (up to 85.5 %) and tannins (31.48 to 41.60 %), improving mineral bioavailability [33, 40].

These biochemical changes lead to substantial enhancements in nutritional and functional quality [68], such as:

- Nutrient Enhancement: Protein content increases notably, for example to 22.23 % (40 kHz) and 22.01 % (28 kHz) compared to a control (16.12 %) [40], with another study reporting an increase from 13.12 g/100 g to 15.45 g/100 g [37]. Fiber content also increases significantly, reaching 31.39 % (40 kHz) and 29.71 % (28 kHz) [40]. The mineral profile is enhanced, with optimal conditions for elevating Mg^{2+}, Ca^{2+}, and K^{2+} (28 kHz, 50°C) and Fe^{2+} (40 kHz, 50°C) [60].

Table 4 Emerging technologies applied to Andean pseudocereals and their effects on nutritional composition

Technology	Grain	Parameters	Antinutrients	Bioactive Compounds	Minerals	Ref.
Ultrasound	Quinoa	Various: 28–40 kHz, 30 min; 37 kHz, 30 min; 100 W, 4 min	Phytic acid: −82.99 to −85.5%. Tannins: −41.60%	GABA**:** 9.15× increase (162.47 mg/100 g). Phenolics**:** +10.2 to +35%. Flavonoids**:** +33.6%. PUFA: +14.4%. Antioxidant: DPPH +14.4 to +64%,α-amylase 14.9%,α-glucosidase 24.6%, lipase 20.0%	Increased:Mg^{2+} 142.71–143.59,Ca^{2+} 86.3–86.83,K^{2+} 428.72–448.67 mg/100 g. Fe^{2+}: 5.64 mg/100 g. Zn^{2+}: 3.51 mg/100 g	[39, 40, 60, 61]
Ultrasound	White Quinoa	100 W, 4 min	—	GABA**:** 9.15× (162.47 mg/100 g). Phenolics: +10.2%. Flavonoids**:** +33.6%. PUFA: +14.4%. Antioxidant**:** DPPH 14.4%,α-amylase 14.9%,α-glucosidase 24.6%, lipase 20.0%	—	[61]
High Pressure	Red Quinoa	200–500 MPa	—	—	—	[62]
Cold Plasma	Quinoa	60 kV, 10 min	Saponins & phytic acid: Highest reduction	Highest flavonoids and phenolic compounds	—	[63]
Magnetic Field	Quinoa	10 mT, 10 min	—	Phenolics: +20.48%. Phenolic acids: +26.54%	—	[64]

Scientific names: Quinoa (*Chenopodium quinoa Willd.*), White Quinoa (*Chenopodium quinoa Willd.*), Red Quinoa (*Chenopodium quinoa Willd.*). Abbreviations: GABA (γ-aminobutyric acid), PUFA (Polyunsaturated Fatty Acids), DPPH (2,2-Diphenyl-1-picrylhydrazyl)

- Bioactive Compound Accumulation: The stress from sonication stimulates the synthesis of secondary metabolites. Total flavonoid content (TFC) increases between 8.1 and 58.2 % [40], and phenolic content increases by 8 % after 24 h germination [39]. Specific treatments favor the accumulation of compounds like rutin, quercetin, kaempferol, hydroxycinnamic, and hydroxybenzoic acids [60, 69], and can cause a 9.15-fold increase in GABA (162.47 mg/100 g) under optimal conditions [61]. This correlates with higher antioxidant capacity: DPPH activity exceeded 50 %, FRAP reached 10.37 μmol TE/g (28 kHz), and ABTS peaked at 15.34 μM TE/g (40 kHz) [40].
- Techno-Functional Properties: The structural modifications, such as extensive fragmentation, surface erosion, increased cell wall porosity, and starch/protein modifications, induced by ultrasound pretreatment [40, 60] improve technological quality. These changes lead to faster hydration and enzyme access. For bakery applications, integrating ultrasonically germinated quinoa into bread formulations results in a higher specific loaf volume and a crumb with reduced firmness due to more efficient hydration and a lower tendency for starch retrogradation [70].

5.1.3 Limitations and implications for product development

Despite the clear nutritional benefits of quinoa, research on using ultrasound for kañiwa and kiwicha remains very limited [6, 32]. Important gaps exist in understanding how the grain survives under strong ultrasound, since too much power can kill the embryo [61]. Also, moving from lab methods to large-scale production is difficult due to the need for strict control of conditions, avoiding microbial contamination, and assessing whether the technology is economically practical in real factories [17, 21].

When it comes to making new food products, studies have mostly looked at changes in composition and metabolites. There is not enough solid data on key processing factors like how fast the grain absorbs water, how the dough behaves, or detailed sensory tests with trained tasters [17, 70]. So, even though the biochemical changes suggest better technical properties, whether this actually works in real products and whether consumers will accept them is not yet fully proven in the scientific literature [17, 30].

5.1.4 Comparative remarks and research gaps

Despite consistent improvements in protein, phenolic compounds, and phytic acid reduction, the magnitude of these effects varies considerably across studies (protein increase from 15.5 to 38.0 %; phytic acid reduction from 63.0 to 85.5 %). These differences likely reflect variations in ultrasound frequency (28–40 kHz), exposure time (4–30 min), and drying temperature. More importantly, all available studies focus exclusively on quinoa; no reports were found on ultrasound-assisted germination of kañiwa or kiwicha. This limits any generalisation of the technology's efficacy to other Andean grains.

5.2 High hydrostatic pressure

5.2.1 Principle and optimization strategies

High hydrostatic pressure (HHP) is a non-thermal technology that employs hydrostatic pressure, commonly in the range of 100 to 800 MPa, for food processing and preservation [71]. It is important to note that while HHP is generally considered a non-thermal technology, adiabatic compression during the process can generate a moderate

temperature increase. This effect may contribute to structural and functional modifications in food components and must be considered when interpreting treatment outcomes. As a promising approach to enhance the nutritional quality of whole grains during germination [21], its efficacy depends on careful parameter optimization. The response is highly matrix-specific; for instance, evidence from pseudocereals like buckwheat (*Fagopyrum esculentum*) shows that improper parameters can lead to a loss of functionality or even structural damage to starch and proteins, underscoring the need for tailored optimization for each grain type [72, 73]. The synergy between germination time and HHP duration is a crucial optimization factor, as an appropriate balance can accelerate mass transfer and stimulate the activity of key enzymes (glutamate decarboxylase, GAD), demonstrably capable of radically improving the functional profile and nutrient bioaccessibility of food [73, 74]. However, studies on its application to germinated quinoa, kañiwa and kiwicha remain scarce.

5.2.2 Mechanisms and effects on germination biochemistry

HHP acts as a controlled abiotic stress elicitor that reprograms grain cellular metabolism, inducing biochemical alterations that optimize its nutritional, bioactive, and techno-functional profile [21, 75]. It exerts controlled physical stress that stimulates key metabolic mechanisms, leading to significant shifts in these properties.

- Enzyme Activation and Membrane Permeabilization: The application of isostatic pressure facilitates enzyme-substrate interaction by inducing the permeabilization of cell membranes and partial degradation of internal structures [66]. This mechanism is central to the accumulation of secondary metabolites. For instance, in germinated brown rice, treatment at 60 MPa for 5 min maximized GABA accumulation (121.21 mg/100 g) by promoting the decarboxylation of L-glutamic acid via glutamate decarboxylase (GAD) [21, 76]. Similarly, moderate pressure conditions, such as 30 MPa, have been shown to significantly increase levels of GABA, arabinoxylan, tricin ether, and γ-oryzanol in cereal matrices [74].
- Metabolite Shifts and Bioactive Compound Synthesis: HHP acts as an elicitor, boosting key metabolic pathways like the phenylpropanoid pathway for flavonoid production as a defense mechanism against mechanical stress [21, 77]. This leads to a marked increase in phenolic content and antioxidant activity. In germinated brown rice, increasing pressure up to 100 MPa progressively increased total phenolic content (from 85.37 to 183.52 μg GAE/g), a nearly 70 % improvement, enriching compounds like catechins [21, 75]. A 400 MPa treatment also increased total phenols and antioxidant activity (FRAP) [21, 78].
- Protein Modification and Techno-functional Properties: In germinated Andean pseudocereals, HHP treatment at 200–500 MPa acts synergistically with germination to induce controlled protein denaturation and starch granule amorphization [16, 72]. Specifically, for germinated red quinoa, this synergy significantly enhances functional properties through protein denaturation and exposure of hydrophobic sites, leading to a marked increase in oil absorption capacity (80.86 %) and emulsification capacity (64.17 %). This biochemical process exposes hydrophobic sites and modifies the quaternary structure of proteins. The result is a significant enhancement of techno-functional properties critical for food applications, namely, a substantial increase in oil absorption and emulsification capacities. These improved attributes are essential

for the stability of complex food systems and the development of products like gluten-free bakery items [62, 66].

5.2.3 Limitations and implications for product development

While HHP has potential for optimizing germinated grains, its implementation involves limitations that affect product development [79]. A key constraint is the inhibition of embryonic growth at elevated pressure levels, which can reduce seed viability and create a trade-off between increasing bioactive compound synthesis and maintaining germination yield [76, 77].

The matrix-specific nature of HHP responses hinders the standardization of processing protocols [72, 76]. Parameters optimized for cereals such as rice or buckwheat are not directly applicable to Andean pseudocereals like kañiwa or kiwicha, whose distinct pericarp structures and molecular compositions require specific validation [78].

For food industry applications, the observed increases in phenolic content and antioxidant capacity can improve the nutritional profile of bakery products and snacks [30, 78]. Pressure-induced enhancements in oil absorption and emulsification capacities may also modify dough rheology and stability, affecting final product texture and moisture retention [62]. However, sprouting inhibition could lower flour yield and alter flavor development, requiring process designs based on multivariate optimization [44, 45].

5.2.4 Comparative remarks and research gaps

Evidence on HHP-assisted germination of Andean pseudocereals remains indirect. Most studies refer to rice or buckwheat, where moderate pressures (30–60 MPa) consistently increase GABA and phenolic content, whereas higher pressures (>100 MPa) reduce seed viability. Within the reviewed literature, only one study on red quinoa reported improved functional properties [62]. Whether these effects occur in kañiwa or kiwicha, and what pressure thresholds are suitable for these smaller grains, remains unknown.

5.3 Cold plasma

5.3.1 Principle and optimization strategies

Plasma, the fourth state of matter, is a partially or fully ionized gaseous mixture containing highly reactive species, including reactive oxygen species (ROS), reactive nitrogen species (RNS), and radicals [21]. In food applications, cold plasma (CP) technology utilizes these high-energy free ions and electrons to induce chemical and structural modifications [80]. Its application on seeds is dose-dependent and varies by cultivar, requiring careful optimization of parameters such as exposure time and the type of gas used for plasma generation (oxygen, air, argon, or helium) [81–83]. Optimization strategies may consider factors such as pre-soak conditions, seed moisture, and the potential for iterative treatments to achieve desired effects without compromising seed viability.

5.3.2 Mechanisms and effects on germination biochemistry

The primary mechanisms of CP on seeds include surface etching and functionalization, which improve water uptake and can act as a signaling trigger for stress responses [83]. These physical and chemical interactions influence germination biochemistry through several pathways:

- Cell Wall Permeability: Surface etching increases cell wall porosity, facilitating faster hydration and potentially improving access for enzymes during germination and processing.
- Enzyme Activation and Antinutrient Reduction: CP treatment can activate the seed's antioxidant systems and reduce antinutritional compounds. For instance, treatment of quinoa grains at 60 kV/10 min reduced saponins and phytic acid while improving flavonoid content, though it decreased some phenolic compounds and antioxidant capacity (DPPH and FRAP) [63].
- Metabolite Shifts and Microbial Safety: The generation of ROS and RNS confers notable antimicrobial potential, inactivating bacteria, molds, yeasts, spores, and viruses on food surfaces [81]. This, combined with the reduction of thiobarbituric acid reactive substances (TBARS), helps maintain a balance between microbiological safety and nutrient preservation [63]. The metabolic shifts induced can precondition seeds, significantly improving seedling resilience and uniformity, especially under stress, when used as a short-duration "priming" agent (30 s) [82].

These biochemical changes are consequential for food applications. For example, modifications to grain components, evidenced in processed quinoa flour, which showed altered functional properties like water absorption [84], can directly impact downstream processing. Enhanced hydration and enzyme access could modify starch and protein structures, ultimately influencing dough viscoelasticity, crumb structure in bakery products, and other techno-functional properties.

5.3.3 Limitations and implications for product development

Despite its promise, the effects of CP on germinated Andean whole grains remain underexplored. From a sustainability perspective, CP is a clean technology as it requires no water or additional chemicals, generates no toxic by-products, and has low energy consumption, offering a sustainable alternative for food processing [85]. However, its application has limitations and specific implications for product development:

- Dose-Dependent Effects: The dual effects observed in quinoa–where some bioactive compounds are enhanced while others are diminished–highlight the need for precise, application-specific optimization to avoid negative impacts on nutritional profile, antioxidant capacity, or sensory attributes.
- Impact on Functional Properties: Changes induced in flour, such as water absorption, directly affect dough rheology, hydration requirements, and final product texture. These must be carefully managed in product formulations.
- Sensory Considerations: While not explicitly studied in the provided literature, the structural and chemical modifications caused by CP could influence color, flavor, or mouthfeel, requiring sensory evaluation.

The most promising application for germination may be as a "priming" agent to improve seedling vigor. However, the technology's broad effects necessitate a holistic view to leverage its benefits for microbial safety and functional modification while mitigating potential drawbacks in nutritional and product development contexts.

5.3.4 Comparative remarks and research gaps

Although cold plasma technology has been studied in quinoa, the literature remains limited. Recent studies have applied plasma before germination with varied results [82, 83]. While germination alone significantly reduces phytic acid [19], the effect of plasma on secondary metabolites is complex; for instance, an increase in saponin content and antioxidant enzyme activity has been reported following plasma treatment [82], which contrasts with the typically sought reduction of antinutrients. This variability, combined with findings in other grains, such as rice, illustrates the contrasting effects of cold plasma. While some studies report that plasma reduces phenolic content in rice [86], others have demonstrated significant accumulation of bioactive compounds, with GABA levels reaching up to 28 mg/100 g after high-intensity treatments (3000 kV/10 min) [87, 88]. This highlights that plasma conditions require precise optimisation and are variety-dependent. Currently, no studies are available on the application of cold plasma to kañiwa or kiwicha.

5.4 Magnetic field

5.4.1 Principle and optimization strategies

A magnetic field (MF) is the space of influence where forces from a magnet or electric current can modify or induce magnetism in nearby bodies. First proposed as a non-thermal food preservation alternative in Hofmann's patent, it has since been identified as a suitable method to favor seed germination processes [22, 89]. Optimization is critical, as the effect is specific to magnetic strength. For example, a field of 5 mT is effective for boosting key enzymes in quinoa, whereas different strengths may be ineffective or even hinder germination [90]. Key optimization parameters include field strength (5 mT, 10 mT) and exposure time (10 min). The technology's scalability presents a challenge, as large-scale farm applications would require specialized equipment [90].

Recent research has introduced a nuanced strategy in magnetic applications: the use of magnetized water as an indirect treatment method. This involves exposing irrigation water to a magnetic field (2.8 Gauss for 2 h) so that it retains residual magnetism and altered physical structure [91]. This approach offers a potentially more energy-efficient and scalable alternative to exposing seeds or plants to a direct, continuous field. Furthermore, optimization strategies are evolving to consider synergistic combinations. Studies show that while magnetized water alone improves outcomes, the most significant gains are achieved when it is combined with a direct magnetic field, suggesting a multi-layered approach to maximizing biostimulation [91].

5.4.2 Mechanisms and effects on germination biochemistry

The application of MF acts as a biostimulant, primarily influencing germination through metabolic activation. As summarized in Table 4, specific treatments, such as a 10 mT field applied for 10 min, have been shown to be effective in quinoa grains. The primary mechanism behind this effect involves the activation of the phenylpropanoid pathway, a biosynthetic route starting from phenylalanine that leads to the production of a wide range of bioactive compounds and a reinforced antioxidant capacity to stimulate enzymes and defense mechanisms [92]. MF treatment enhances the activity of key enzymes. For instance, applying a 5 mT field during quinoa germination boosts enzymes involved in the synthesis of γ-aminobutyric acid (GABA) and strengthens the seed's

endogenous antioxidant defenses, resulting in more nutritious sprouts [90]. This optimizes metabolic processes, leading to more marked increases in bioactive compounds that intensify with germination time [93]. The positive biostimulant effects are amplified when MF pretreatment is combined with other stressors, such as moderate salt stress (NaCl), improving growth and enriching the profile of secondary metabolites [64].

At a biophysical level, these effects are rooted in the ability of magnetic fields to alter cell membrane permeability and ion transport channels. This facilitates a more efficient uptake of water and nutrients, a mechanism that is dramatically illustrated by the use of magnetized water. For instance, quinoa seeds hydrated with magnetized water achieved 63.60 % water absorption compared to 46.00 % in the control. When this was combined with a direct magnetic field, absorption nearly doubled to 98.13 %, directly correlating with a significant increase in sprout biomass and dimensions [91].

These biochemical changes are important for food applications because they directly enhance the nutritional and functional profile of germinated grains. By increasing bioactive compounds, antioxidants, and compounds like GABA, MF-treated sprouts are positioned as ingredients with higher biological value for functional foods.

5.4.3 Limitations and implications for product development

While promising for quinoa, no information was recovered on the application of magnetic fields in kañiwa and kiwicha, indicating a significant research gap for Andean pseudocereals. The main limitations and implications are the precise dosage requirement, as efficacy is highly dependent on a specific magnetic strength, requiring precise calibration to avoid null or negative effects on germination [90]. Furthermore, technological and scalability challenges exist, as implementing this technology on an industrial scale requires significant investment in specialized equipment [90]. Another critical limitation, highlighted by recent findings, is the genotype-dependent response. The effectiveness of magnetic treatment is not universal and can vary significantly between different quinoa ecotypes. For example, a Peruvian variety showed a much stronger positive response (greater weight gain and sprout dimensions) to the same magnetic treatment compared to an Iranian variety [91]. This implies that optimization protocols must be tailored not only to the species but potentially to the specific genetic line being used. Regarding implications for functional food development, the integration of MF into the value chain of Andean pseudocereals can promote their consumption by enhancing their functional properties. The technology increases bioactive compounds and antioxidant capacity, which could influence nutritional labeling, health claims, and potentially the sensory profile (reduced oxidation off-flavors) of final products. However, these potential sensory impacts require direct study.

Overall, MF presents a targeted, non-thermal strategy to biostimulate germination and improve grain quality, though its application is currently limited by precise optimization needs, genotype-dependent efficacy, and scalability constraints.

5.4.4 Comparative remarks and research gaps

The application of magnetic fields to germinated quinoa in the reviewed literature is limited to two recent studies [64, 93]. One study reported significantly increased GABA and antioxidant enzyme activity at 5 mT [93], while another utilized a 10 mT pretreatment to enhance phenolic biosynthesis and antioxidant enzyme systems, demonstrating synergy

with moderate salt stress (100 mM NaCl) [64]. A third, very recent study adds a crucial layer of understanding by exploring the use of magnetized water and demonstrating the profound impact of magnetic fields on physical water uptake and biomass gain, with effects varying by genotype [91]. This introduces a new variable (genetic diversity within a species) and a new application method (magnetized water) that warrant further investigation. However, effective field strength appears to be narrow and study-dependent, scalability remains unaddressed, and no data on metabolic enhancement exist for kañiwa or kiwicha, despite isolated germination trials in amaranth [89]. The discovery that very low-intensity fields (in the Gauss range, as opposed to the milli-Tesla range used in other studies) can be effective when applied indirectly through water [91] opens new avenues for low-cost, energy-efficient technological development, a critical factor for scalability.

5.5 Other treatments

Beyond the core emerging technologies, exposure to ozone has been explored as a viable alternative. In kiwicha, ozone treatment during germination increased protein content (18.5 %), dietary fiber (25.7 %), phenolic compounds (34.2 %), flavonoids (29.6 %), and antioxidant activity (41.8 %) [94, 95]. Notwithstanding these benefits, ozone requires stringent control due to its high oxidative capacity and regional regulatory restrictions, with some jurisdictions limiting its use to disinfection processes [95].

Regarding metabolic resilience, the enrichment of quinoa seeds with B-complex vitamins during germination has been shown to enhance proline accumulation and protect against oxidative stress [96]. Moreover, the synergy between germination and fermentation in quinoa proved highly effective, increasing protein (17.21 g/100 g d.m.) and phenol content (276.9 mg GAE/100 g), while drastically reducing phytates (73 %) and saponins (from 11.20 to 0.15 mg/g) [79].

As for chemical-physical interactions, thermoalkaline pretreatments (NaOH 1 %, 30°C) demonstrated superior efficacy in reducing tannins, with decreases of 83 % in buckwheat and 20 % in quinoa [39]. Finally, the germination-enzymatic hydrolysis sequence in amaranth generated hydrolysates with low molecular weight bioactive peptides and high antioxidant activity (1304.9 μmol TE/mg d.b.), highlighting the potential of these combined biotechnologies to develop high-value functional ingredients [97].

5.6 Practical and industrial considerations for emerging technologies

Despite the promising biochemical and functional effects of non-thermal technologies on germinated Andean pseudocereals, their transition from laboratory-scale experiments to commercial applications requires evaluation of industrial scalability, economic feasibility, food safety, regulatory status, and sensory implications. This section addresses these practical considerations, which remain insufficiently discussed in the current literature.

5.6.1 Industrial scalability

Although increasing interest in emerging technologies remains at experimental stages, HHP currently constitutes the non-thermal technology with the highest degree of global commercialisation [66, 98]. Industrial HHP equipment available on the market presents processing capacities ranging from 525 litres to 3000 kg per hour, enabling its integration

into medium- and high-capacity production lines [66]. In the case of ultrasound, industrial viability has been demonstrated through its integration into defoaming and food extrusion processes, where it optimises the efficiency of conventional unit operations [65]. Regarding cold plasma, the development of systems operating at atmospheric pressure has eliminated the need for vacuum equipment, facilitating its implementation in industrial environments [66]. Magnetic field treatment has been consolidated as a methodology for improving seed germination vigour, distinguished by its operational simplicity as it requires no direct physical contact with the biological material nor generates ionic residues in the final product [89, 93].

However, specific scalability data for Andean pseudocereals remain absent. The differential responses of quinoa, kañiwa, and kiwicha to these technologies – derived from their distinct pericarp structures, seed sizes, and chemical compositions – require grain-specific validation before industrial transfer can be recommended.

5.6.2 Cost and energy requirements

The industrial adoption of HHP faces as its principal limitation the high initial capital investment, with complete equipment costs ranging between 500,000 and 2.5 million USD [66]. Comparative economic analysis studies in citrus juices have established that HHP processing implies a cost approximately seven times higher (10.7 US cents per litre) than conventional thermal pasteurisation (1.5 US cents per litre), attributable mainly to electrical consumption and depreciation of capital invested in specialised equipment [98]. Research indicates that incorporating regenerative pressure recovery systems can reduce operating expenses by 30 to 40 % [77].

Ultrasound is positioned as an energetically favourable alternative, classified within clean-processing technologies. Specific measurements have recorded consumptions of 8.608 kWh for treatments at 40 kHz under optimised operating conditions [40, 65]. Cold plasma operating at ambient temperature offers economic benefits derived from energy savings, with reports of 40 % reductions in energy consumption during drying processes compared to control treatments without cold plasma application [99]. Magnetic fields represent a low operational cost option for inducing metabolic responses during germination, with no requirement for additional chemical inputs [89].

For Andean pseudocereals, cost-benefit analyses are not currently available in the peer-reviewed literature. The higher market value of these grains and their positioning in functional food segments may justify additional processing costs, but this remains a hypothesis requiring empirical validation through techno-economic assessments.

5.6.3 Food safety and regulatory considerations

The guarantee of food safety constitutes a differential advantage of HHP, given that pathogen inactivation is achieved at near-ambient temperatures, a condition that simultaneously preserves the integrity of nutritionally relevant compounds [66, 98]. Cold plasma has demonstrated the capacity for microbial load reduction and degradation of chemical contaminants such as mycotoxins and pesticide residues in food matrices [80]. However, the regulatory implementation of cold plasma faces obstacles derived from insufficient long-term human toxicological data. Particularly regarding the safety of compounds generated by reactions between plasma reactive species and food surface components [66, 99].

Magnetic field treatment, as a physical non-contact process without chemical residue generation, presents fewer regulatory barriers [89]. A common limitation across these technologies is the absence of regulatory frameworks specifically addressing their application to germinated products destined for gluten-free or functional food claims. No studies have evaluated the potential migration of packaging components or degradation products when these technologies are applied to pre-germinated grains intended for long-term storage.

5.6.4 Effects on sensory quality and consumer acceptance

HHP treatment enables the preservation of freshness attributes, colour profile, and original organoleptic characteristics of products, minimising micronutrient losses associated with conventional thermal treatments [72]. The germination process itself improves the sensory acceptability of Andean grains. In quinoa, saponin content reduction decreases bitterness and astringency perception [50, 70]. The generation of reducing sugars during germination contributes to masking unfavourable flavours, improving the gustatory profile of the final product [4].

Nevertheless, ultrasound application requires precaution in matrices with high lipid content due to the potential induction of auto-oxidation reactions that generate volatile compounds responsible for unpleasant flavours [66]. Similarly, cold plasma application must be carefully parameterised to avoid lipid oxidation that would compromise the sensory quality of the processed product [99]. For kañiwa and kiwicha, no sensory studies have been conducted on products derived from grains treated with these non-thermal technologies. Consumer acceptance studies specifically evaluating the impact of technology-assisted germination on perceived quality, willingness to pay, and purchase intention are absent from the current literature.

5.7 Synergistic non-thermal treatments

Ultrasound is the most extensively studied of the four technologies, with consistent evidence of improved nutritional and antinutritional parameters in quinoa. In contrast, HHP, cold plasma, and magnetic fields remain at early stages, each supported by only a few studies and showing variable effects on bioactive compounds. A common limitation across all technologies is the substantial lack of data on kañiwa and kiwicha, which restricts any generalisation to these understudied grains. Furthermore, no experimental studies have yet applied sequential combinations of these technologies to Andean pseudocereals. This gap likely reflects the high cost of multi-technology equipment and the complexity of optimising multiple variables. However, combining these technologies could address the limitations of individual treatments by pairing complementary mechanisms, such as surface modification followed by enhanced mass transfer.

Table 5 outlines three theoretically supported combinations for this purpose. Among them, cold plasma followed by ultrasound appears most promising, as it sequentially addresses surface hydrophobicity and internal water movement, two key barriers to efficient germination in these grains. The continuous operating nature of both technologies also suggests higher practical feasibility for integration.

Table 5 Proposed synergistic combinations of non-thermal technologies for Andean grains

Combination	Rationale & mechanism	Expected outcome	Ref.
CP + US	CP pre-treatment etches seed surface, increasing hydrophilicity. Follow-up US uses cavitation to enhance water/nutrient uptake	Faster germination and significantly higher GABA accumulation for functional malts	[21, 61, 83]
MF + HHP	MF stimulates metabolism during germination. A subsequent moderate HHP pulse stresses sprouts, inhibiting growth but upregulating defense pathways	Biofortified "dwarf" sprouts with high concentrations of antioxidants like polyphenols	[89, 93]
US + HHP	US during germination improves digestibility. HHP treatment of the resulting flour modifies proteins and starch, creating new structural networks	Flour with improved techno-functional properties for gluten-free baking	[16, 72]

CP = Cold Plasma; US = Ultrasound; MF = Magnetic Field; HHP = High Hydrostatic Pressure; GABA = γ-aminobutyric acid

6 Application of germinated grains in gluten-free baked products

With celiac disease affecting approximately 1 % of the global population [100], and approximately 1.20 % of Peruvians aged 18 to 29 [101], the demand for high-quality gluten-free products has increased substantially. However, gluten-free bakery products currently available exhibit well-documented technological and nutritional shortcomings: dense crumb structure, pale crust coloration, rapid staling, low protein and dietary fiber content, and high glycemic index [11, 102, 103]. These limitations arise fundamentally from the absence of gluten's viscoelastic network, which in wheat-based systems provides gas retention, water binding, and structural integrity. Gluten-free formulations typically rely on starch-based flours, hydrocolloids, and emulsifiers to approximate these functions–approaches that address rheology but not nutritional inadequacy. Germinated Andean pseudocereals offer a dual solution: their modified starch and protein fractions contribute to dough performance while simultaneously enhancing protein, fiber, and mineral content [14–16].

6.1 Formulation strategies and product development

As synthesized in Table 6, the functional performance of germinated Andean pseudocereals critically depends on the formulation strategy rather than their isolated use. Combinations of germinated quinoa with germinated corn flour, together with optimized water dosing, consistently improve specific volume, cohesiveness, and elasticity [104]. These synergistic effects yield crumb structures and sensory acceptability scores comparable to or exceeding 7 on a 9-point hedonic scale, demonstrating that germinated grains function best as part of multi-component systems. Detailed formulation conditions are provided in Table S3 (Supplementary Material).

6.2 Influence of germination on dough rheology, texture, and sensory quality

From a technological perspective, the functional improvements originate from germination-induced rheological weakening. As detailed in Sect. 4, germination activates enzymatic pathways that degrade reserve compounds, including the hydrolysis of starches and proteins. This biochemical modification reduces dough viscosity and diminishes starch retrogradation, which is quantitatively associated with lower setback values [37, 70, 105]. This partial hydrolysis produces softer crumb texture and delays staling during storage [17, 37, 70].

Concurrently, proteolysis generates free amino acids and peptides that act as Maillard precursors during baking, enhancing crust color and promoting volatile compounds associated with roasted, nutty, and malty aromas, effectively masking the grassy off-notes typical of raw pseudocereal flours [70, 106]. Solubilization of dietary fiber fractions increases water absorption and contributes to dough cohesiveness and extensibility, partially compensating for the absence of gluten [104, 106, 107]. The concurrent reduction of anti-nutritional factors (saponins, phytic acid) minimizes bitter aftertastes, directly translating into higher hedonic acceptability scores [19, 70, 108].

Collectively, these biochemical transformations enable superior functional products tailored for consumers with special dietary needs [43].

Table 6 Application of germinated Andean pseudocereals in gluten-free products

Grains & conditions	Key improvements	Product	Main findings	Ref.
Quinoa (50–90%) + Germinated tarwi/fenugreek (5–20%) + Corn (10%)	Enhanced nutritional profile & sensory properties. Optimal: 60% quinoa, 15% lupin, 15% fenugreek, 10% corn	Multigrain bread	Improved protein & dietary fiber content	[111]
Germinated quinoa/kañiwa/kiwicha (20–40%)	GABA: 2.7–8.9×. TPC: +23–67% (472 mg GAE/100 g). ORAC: 1.2–6.4×. GI: 81.4 vs 87.7	Cookies	Bioactive compounds maintain bioaccessibility after digestion	[32]
Quinoa flour (20%), Germinated quinoa (20%), Quinoa sourdough (30%)	Sensory: GQ highest acceptability (5.76/9). Texture improved. Shelf life: QSD 6 days, GQ 4 days	Bread	QSD optimizes protein, texture & shelf life. GQ better sensory acceptance	[109]
Kiwicha (5%) + Kañiwa (23.1%) + Wheat (71.9%)	GABA: 18 mg/100 g. TPC: 237 mg GAE/100 g. ORAC: 66 μmol TE/g. Sensory >7/9. GI: 83 vs 93	Bread	Benefits maintained after digestion. Low GI product	[45]
Quinoa germinated fermented (20%)	Protein digestibility: 71–77%. GI: 57–76%. Improved sensory properties	Bread	Germination + fermentation biofortifies flour. Increases digestibility, reduces GI	[106]
Germinated corn/quinoa/millet/fenugreek	Protein: +54%. Fiber: +39%. Minerals increased. Antioxidant: 45%. TPC: 72 mg/100 g. Sensory $\geq$7/9	Crackers	Improves nutritional density. Viable for pediatric gluten-free products	[112]
Quinoa + Corn mixtures	Texture: Better cohesiveness/elasticity. Acceptability optimal. 100% quinoa low acceptance	Bread & Cake	Germination optimizes functional properties. Mixtures improve texture & sensory	[104]
Chenopodium album (100%)	Antioxidant: +24%. TPC: 671 mg GAE/100 g. Fiber: 39 g/100 g. Sensory: 7.75/9 vs 6.50/9	Cookies	Germination improves nutritional profile. Higher functional & sensory quality	[113]
Quinoa (20% optimal)	Fermentation: Gas retention 90%, Volume 3.61 mL/g. Texture: Firmness 5.6 N. Reduced bitterness	Enriched bread	Improves baking & sensory properties. Viable for high-value products	[70]
Kiwicha (100%)	Fiber: 14 g/100 g. Antioxidant: 21 g/100 g. Hardness: 42 N. Sensory: 7.5/9	Cookies	Germination improves nutritional & functional attributes. Enhances gluten-free products	[114]
Germinated kiwicha/millet/corn/lentils/lupin/peas/quinoa (5%)	Specific volume: 3.01 vs 2.42 mL/g. Crumb hardness: 3.50 vs 5.77 N	Bread	Consistently improves bread quality. Multifactorial matrix interactions	[107]

Scientific names: Quinoa (*Chenopodium quinoa Willd.*), Kañiwa (*Chenopodium pallidicaule Aellen*), Kiwicha (*Amaranthus caudatus L.*). Abbreviations: GABA (γ-aminobutyric acid), ORAC (Oxygen Radical Absorbance Capacity), TPC (Total Phenolic Content), TFC (Total Flavonoid Content), DPPH (2,2-diphenyl-1-picrylhydrazyl). Units: GAE (Gallic Acid Equivalents), TE (Trolox Equivalents)

6.3 Challenges and limitations

Four interrelated challenges constrain industrial adoption. First, uncontrolled enzymatic activation, particularly of amylases and proteases, can excessively degrade starch and proteins, causing loss of viscosity, consistency, and gelling capacity. This necessitates precise control of germination conditions or post-germination thermal treatments to partially inactivate enzymes [105, 107].

Second, intraspecific varietal differences (white, red, and black quinoa ecotypes; distinct kañiwa and kiwicha varieties) produce variable responses to soaking, germination, and drying, requiring crop-specific protocol optimization that complicates standardization [19, 41, 43, 46].

Third, partial substitution of gluten-free flours with germinated pseudocereals often necessitates supplementary hydrocolloids, emulsifiers, or enzymes to restore dough rheology, increasing formulation complexity and production costs. This cost barrier disproportionately affects small and medium-sized enterprises [3, 104].

Fourth, germination exerts opposing effects on product shelf life. Partial starch hydrolysis and α-amylase activity reduce retrogradation, delaying crumb firming and maintaining softness during storage [70]. However, germinated flours possess higher moisture content and intrinsic microbial load, which can accelerate mold spoilage. Bread containing germinated quinoa flour exhibited only four days of mold-free shelf life, compared to six days when quinoa sourdough was used [109]. Oxidative stability is also relevant due to unsaturated lipid content in Andean pseudocereals. Predictive models based on lipid oxidation kinetics have been developed for gluten-free crackers [110], and Rancimat methods can estimate shelf life from oxidative stability indices [8]. Emerging preservation technologies, such as hyperbaric storage [66] and cold plasma [99] may extend shelf life without thermal degradation but remain unexplored in germinated Andean grain products.

6.4 Kañiwa and Kiwicha: emerging matrices for novel germinated products

Beyond the extensive research on quinoa, kañiwa and kiwicha present differential biotechnological characteristics that position them as superior matrices for novel functional ingredients. A significant industrial advantage of kañiwa is its non-bitter saponin profile, which eliminates the need for intensive abrasive washing. This allows for a direct industrial transformation that preserves its high iron content (125 $mg{\cdot}kg^{-1}$) and chlorogenic acid (3-*O*-caffeoylquinic acid) levels, the latter being a key phenolic compound associated with glycemic metabolism modulation [2, 6].

Simultaneously, kiwicha offers extraordinary neuroprotective potential. Under optimized germination conditions (26 °C for 63 h), it triggers a GABA biosynthesis increase of up to 29.1-fold, significantly outperforming conventional cereals [52]. Furthermore, kiwicha stands out for its calcium content (1000 $mg{\cdot}kg^{-1}$) and its superior techno-functional attributes in bakery; germinated kiwicha flour produces softer crumbs and higher loaf volumes than germinated quinoa [33, 107].

The binary combination of germinated kañiwa and kiwicha has been validated as a highly effective formulation strategy. Optimization studies have demonstrated that specific proportions of these germinated flours achieve sensory acceptability scores above 7 on hedonic scales while simultaneously reducing the glycemic index and phytic acid content through endogenous phytase activation [45, 52]. These findings demonstrate the

synergy between both matrices, offering a path for the development of clean-label, nutrient-dense products with enhanced technological functionality.

7 Current challenges and future perspectives

7.1 Germination

Over the last decade (2015–2025), germination has established itself as a cross-cutting theme in agricultural, food, and biotechnological research. The analysis of the keyword network (Fig. 2) shows the co-occurrence map, demonstrating that this process is studied from the physiological perspective of the seed and as a strategy to improve the nutritional and functional quality of grains destined for human consumption. The central node "germination" has the highest connection density, highlighting its role as the central axis of the network. Closely related concepts such as "grains", "seed", "cultivation", "metabolism", and "nutrition" are grouped around them, reflecting the multidimensional focus of studies on physiological, biochemical, and technological processes linked to germination. Furthermore, thematic clusters addressing emerging aspects are observed, including "ultrasound", "fermentation", "enzymes", and "plant proteins", which suggest the incorporation of emerging technologies and biotechnological strategies aimed at improving the nutritional and functional quality of germinated grains.

Regarding the most researched crops, rice (*Oryza sativa*), corn (*Zea mays*), and wheat (*Triticum aestivum*) show a higher density of connections with terms associated with seed, metabolism, and cultivation (Fig. 2). These crops dominated most studies due to their strategic role in global food security and wide use in the food industry (baking, malting and fermentation). This reflects their relevance as experimental models in the

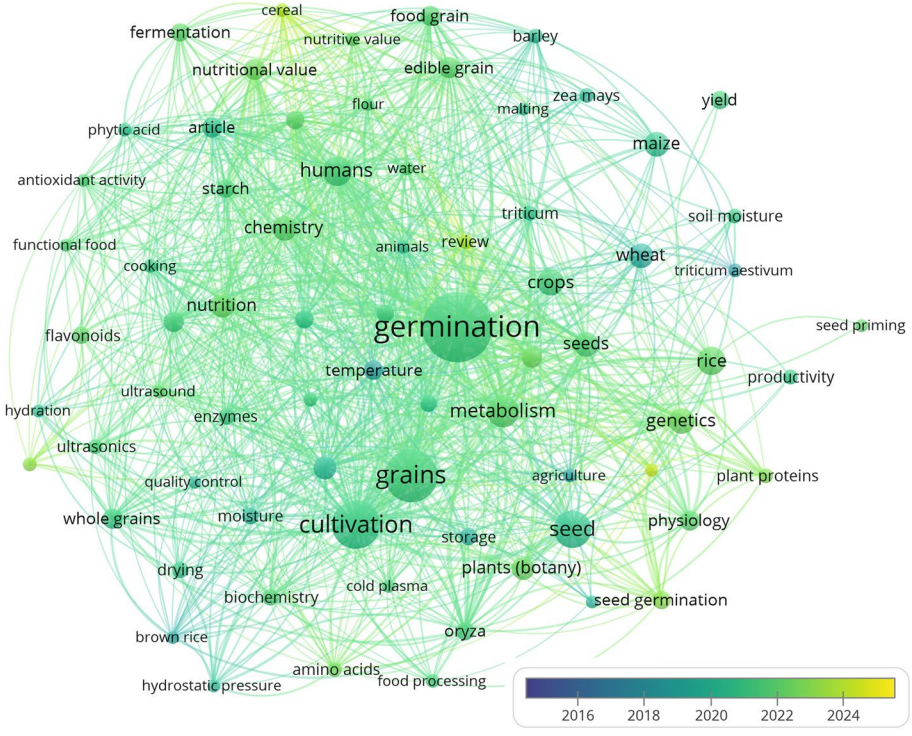


Fig. 2 Scientific production and collaboration on the use of emerging technologies in germinated Andean pseudocereals by country (2015–-2025). Representation obtained using VOSviewer software version 1.6.19, based on a Scopus database search with the equation: ("technology" OR "pretreatment" OR "pre-treatment") AND ("germination") AND ("Andean grains" OR "grains"). The rectangle size represents the research output of each country

optimization of germination processes. Likewise, an increase in the use of emerging technologies applied as pretreatments, including ultrasound, hydrostatic pressure, and cold plasma, aimed at improving germination speed, enzymatic activity, and the availability of bioactive compounds. The concentration of recent studies (green-yellow areas) suggests a trend toward the application of non-thermal physical methods for treating grains for obtaining functional foods.

Regarding scientific production in germination research (Fig. 3), China takes the lead, followed by India. The emerging participation of Peru in recent years is noteworthy, positioning itself as a notable contributor alongside countries like Brazil, the United States, and the Russian Federation, demonstrating significant growth in South American production in this discipline.

However, research on germination using emerging technologies in Andean pseudocereals, particularly quinoa, kañiwa, and kiwicha, remains limited, despite them representing a valuable source of bioactive compounds and high-quality nutrients. Considering this scenario, germination is emerging not only as an essential physiological process for agriculture but also as an important biotechnological and nutritional tool in the design of functional foods and in adapting production systems to the global challenges of food security and climate change.

7.2 Application in gluten-free products

Based on the colors in Fig. 4 obtained with VOSviewer, it can be observed that current research on gluten-free products has evolved from challenges related to base flours toward a priority focus on sensory quality, texture, and nutritional value, including glycemic index control. Consequently, their application in staple products such as bread

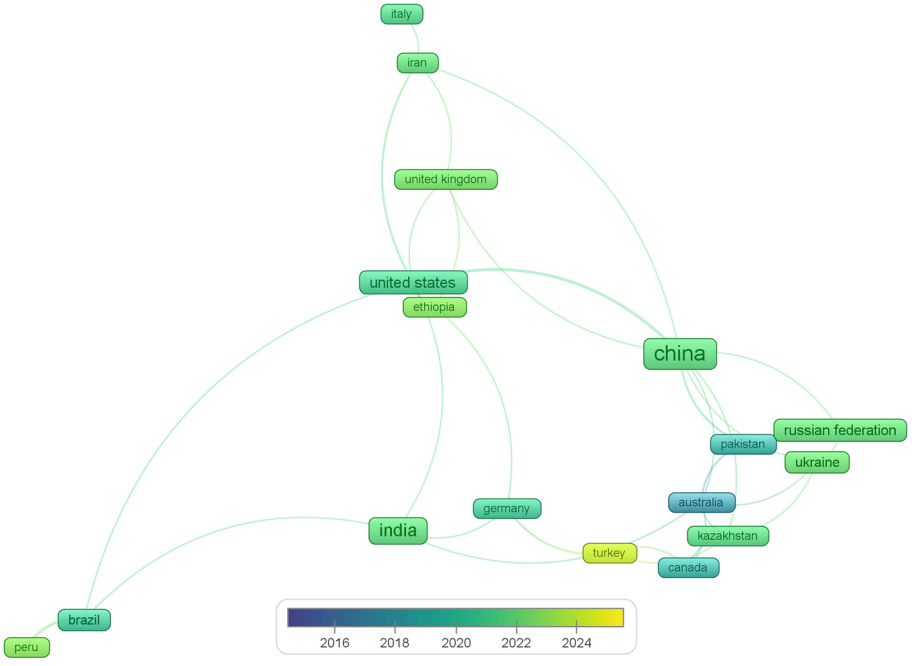


Fig. 3 Scientific production and collaboration on the use of emerging technologies in germinated Andean pseudocereals by country (2015–-2025). Representation obtained using VOSviewer software version 1.6.19, based on a Scopus database search with the equation: ("technology" OR "pretreatment" OR "pre-treatment") AND ("germination") AND ("Andean grains" OR "grains"). The rectangle size represents the research output of each country

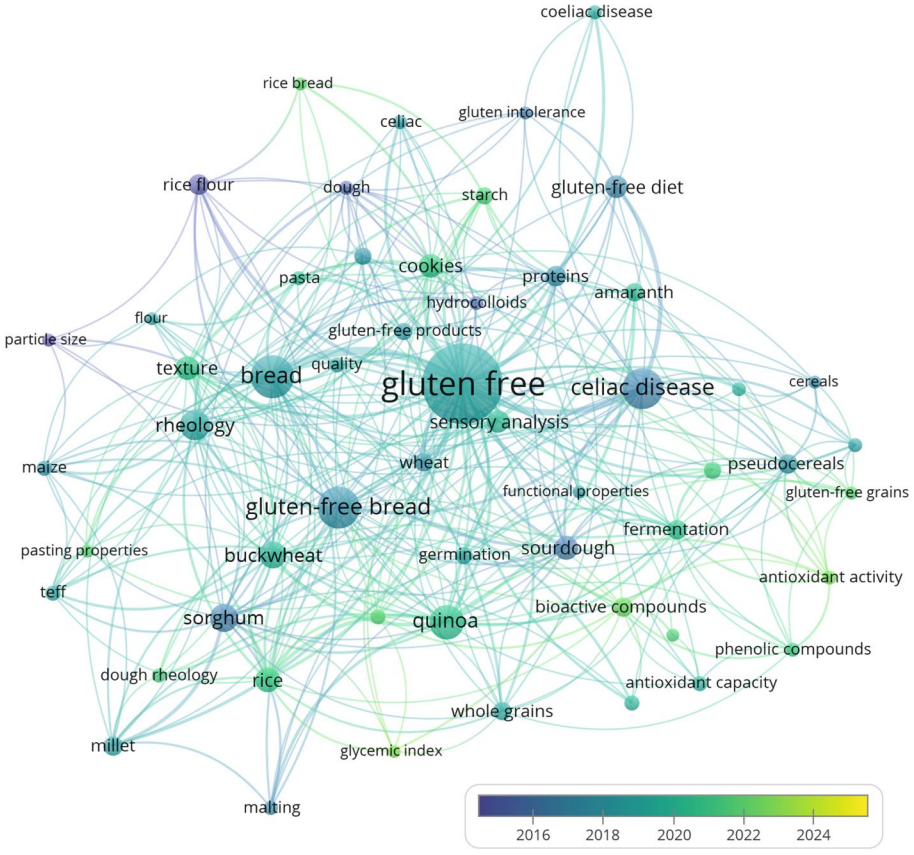


Fig. 4 Clustering by keyword co-occurrence of studies on the application of germinated grains in gluten-free products. Representation obtained using VOSviewer software version 1.6.19, based on a Scopus database search (2015–-2025) with the equation: (germination OR grains OR "Andean grains") AND ("baked goods" OR cookies OR breads OR muffins) AND ("gluten free"). The bubble size represents the frequency of each key term

and biscuits represents an interesting research line. As shown in Fig. 5, scientific leadership in this field comes from countries like Italy and Brazil, and countries like Poland and Peru have also shown growing research interest in these topics in recent years.

The application of germinated Andean pseudocereal flours in gluten-free matrices reveals a consolidated trend toward the fortification of bakery products, where germination emerges as a key biotechnology to enhance the nutritional profile. Furthermore, there is a drive to diversify the applications of germinated Andean pseudocereals beyond traditional products and promote their industrial use through emerging technologies. Thus, germinated Andean pseudocereals are establishing themselves as key functional ingredients for developing of nutritious and gluten-free foods [40, 115, 116].

The main challenge in applying germination technologies to Andean pseudocereals for gluten-free foods lies in improving the technological and sensory properties of the resulting flours [37]. Enzymatic activation during germination breaks down starch and proteins, leading to a significant loss of viscosity, consistency, and gelling capacity, negatively affecting the texture of products such as breads and infant purees [37, 105, 117]. The differences among grain varieties, such as quinoa and kiwicha, complicate industrial standardization and require the optimization of specific conditions for each crop [54]. Furthermore, it is important to maximize nutritional benefits, such as the reduction of

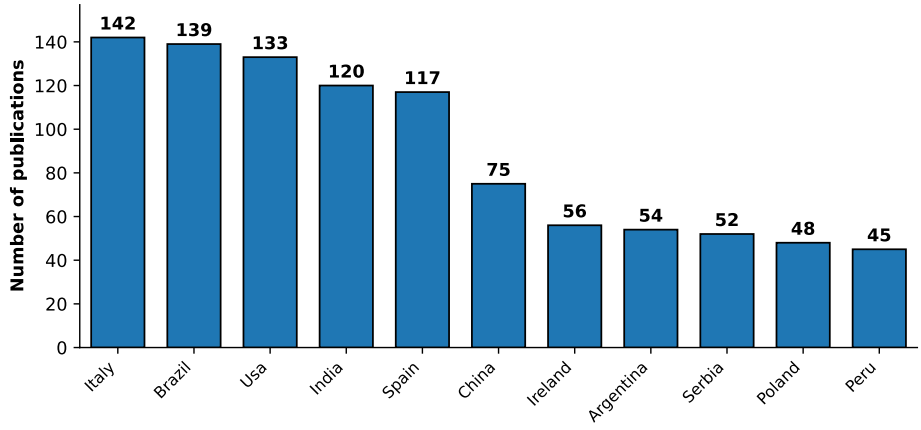


Fig. 5 Leading countries in publishing research on germinated grains in gluten-free products. Data obtained from a Scopus database search (2015–-2025) and analyzed using Biblioshiny, the web interface of the Bibliometrix R-package (version 5.1.0), with the following search equation: (germination OR grains OR "Andean grains") AND ("baked goods" OR cookies OR breads OR muffins) AND ("gluten free")

antinutrients, while avoiding dry matter loss and ensuring the microbiological safety of the final product [38, 48, 57].

The application of high-intensity ultrasound as a pretreatment is emerging as a key strategy to accelerate hydration, reduce drying times, and enhance enzymatic activity, resulting in a greater accumulation of bioactive compounds such as GABA and improved phenol extraction [118]. Protein quality can be improved through sourdough fermentation with selected lactic acid bacteria, which also enhances digestibility, texture, taste, and the shelf life of baked products [119]. Improving bioprocesses can enhance nutritional enrichment by increasing the bioavailability of essential minerals such as iron and zinc through phytic acid degradation, supporting the development of functional foods to combat deficiencies like iron-deficiency anemia [38]. Future research should focus on molecular and metabolomic studies to better understand how germination and processing change protein structures and phytochemical profiles, aiming to improve the nutritional value and consumer acceptance of next-generation gluten-free foods [51, 117].

8 Conclusions

To improve the nutritional and functional value of Andean pseudocereals, germination constitutes a sustainable biotechnological strategy that increases the content of bioactive compounds (GABA, polyphenols, and flavonoids), improves the bioavailability of essential minerals, and reduces antinutrients such as phytic acid and saponins. The integration of emerging non-thermal technologies, such as ultrasound, high hydrostatic pressure, cold plasma, and magnetic fields, optimizes the efficiency of the germination process, boosting the accumulation of secondary metabolites, and improving the techno-functional properties of the resulting flours. These flours enable the production of gluten-free baked goods with superior texture, flavor, and sensory quality, representing a viable alternative to the limitations of conventional products.

However, industrial scalability presents a balance of opportunities and constraints. HHP ensures safety and sensory preservation, although its high investment cost and intensive energy consumption limit its widespread adoption. Ultrasound and magnetic fields offer alternatives with lower operating costs and a reduced energy footprint, whereas cold plasma optimizes energy efficiency but faces regulatory barriers

due to insufficient toxicological data. Consequently, technology selection must balance economic profitability, environmental sustainability, regulatory compliance, and the enhancement of sensory acceptability in gluten-free matrices.

Among the four technologies reviewed, ultrasound is the most studied and shows the most consistent nutritional improvements in quinoa, yet remains unexplored in kañiwa and kiwicha. Establishing optimal processing conditions for these understudied grains through systematic dose–response studies should therefore be a research priority. HHP improves protein functionality but may reduce seed viability. Cold plasma and magnetic fields are less developed, with limited and sometimes conflicting data. Across all technologies, standardised protocols and industrial validation are lacking, and comparisons are hindered by differing conditions and varieties. Future research should prioritise control, head-to-head comparisons to establish reliable benchmarks.

The broader impact of this strategy is best understood through its alignment with the Sustainable Development Goals (SDGs). It contributes to SDG 2 (Zero Hunger) by boosting the nutrient density of climate-resilient crops, offering a viable tool to combat micronutrient deficiencies. The resultant surge in health-promoting compounds directly links to SDG 3 (Good Health and Well-being), supporting preventive nutrition and providing superior dietary options for vulnerable groups, including the celiac population. Furthermore, the adoption of the aforementioned "green" technologies exemplifies SDG 12 (Responsible Consumption and Production), promoting energy-efficient, low-water, and solvent-free processing models essential for a sustainable food industry.

However, translating this promise into global impact requires overcoming key challenges. The primary hurdles are the standardization of germination protocols to ensure consistent metabolic and functional benefits and the validation of health claims through robust *in vivo* studies. Future research must therefore focus on optimizing and scaling these bioprocessing parameters. Ultimately, promoting germinated Andean grains beyond niche raw materials to become cornerstone ingredients in functional foods is not merely a technical advance. It is a strategic step towards building more resilient, circular, and health-focused bio-economies.

Abbreviations

ABTS	2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
DPPH	2,2-Diphenyl-1-picrylhydrazyl
FRAP	Ferric Reducing Antioxidant Power
GABA	γ-Aminobutyric acid
ORAC	Oxygen Radical Absorbance Capacity
TFC	Total flavonoid content
HR	Relative humidity
HHP	High hydrostatic pressure
US	Ultrasound
ROS	Reactive oxygen species
RNS	Reactive nitrogen species
TE	Trolox equivalent
GAE	Gallic Acid Equivalent
QE	Quercetin equivalent
TAA	Total Antioxidant Activity
APCI	Aggregate Antioxidant Capacity Index
TPC	Total phenolic compounds
TBARS	Thiobarbituric acid reactive substances
GAD	Glutamate decarboxylase
cP	Centipoise
dw	Dry weight

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44187-026-01018-4.

Supplementary material. Table S1. Extended data on effects of germination on nutritional composition, bioactive compounds and antinutrients of Andean pseudocereals. Table S2. Extended data on emerging technologies applied to Andean pseudocereals and their effects on nutritional composition. Table S3. Extended data on application of germinated Andean pseudocereals in gluten-free products.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process
During the preparation of this work the author(s) used DeepSeek (V3/R1) in order to assist with English-language translation, grammar, and syntax improvements. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Authors contributions
MD-L: Conceptualization, investigation and original draft writing; BS: Conceptualization, original draft writing, review, and editing; CM: Original draft writing, review, and editing; GS-O: Investigation and original draft writing; EA-R: Investigation, editing, and image preparation.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare no competing interests.

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