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Artículo de investigación

Functional, nutritional, and technological potential of quinoa through lactic acid fermentation: a review

Potencial funcional, nutricional y tecnológico de la quinua a través de la fermentación ácido láctica: Una revisión

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Abstract

Quinoa is an ancestral Andean grain of great importance due to its nutritional potential, cultivated in the Andean region for many years. Lactic acid fermentation may be a cost-effective processing alternative to improve quinoa-derived or gluten-free products, as it has been used in different cereals to enhance physicochemical and sensory characteristics. This review presents the nutritional importance of quinoa, the key indicators that can affect homofermentation, the analysis of different studies that have worked with this pseudocereal as a substrate for the development of various fermented products such as sourdoughs from quinoa flour for bread and other baked goods, beverages, pasta, baked products in combination with other pseudocereals and buckwheat, and soy-based beverages. The results reveal that quinoa is a nutrient-rich substrate for lactic acid bacteria, and fermentation generates nutritional changes by increasing certain macronutrients and/or bioactive compounds through bacterial metabolism and starch hydrolysis. Additionally, it improves functional, technological, and sensory properties due to starch modification and metabolite production. This presents a promising alternative in quinoa processing and the development of functional foods.

Resumen

La quinua es un grano andino ancestral de gran importancia por su potencial nutricional, cultivado en la región andina desde hace muchos años. La fermentación ácido láctica puede ser quizás una alternativa de procesamiento rentable para mejorar productos derivados de quinua o libres de gluten, ya que ha sido utilizada en diferentes cereales para mejorar características fisicoquímicas y sensoriales. Esta revisión presenta la importancia de la quinua a nivel nutricional, los indicadores básicos que pueden afectar una homofermentación, el análisis de diferentes estudios que han trabajado con este pseudocereal como sustrato para el desarrollo de diferentes productos fermentados, como masas madre a partir de harinas de quinua para elaboración de pan y otros productos horneados, bebidas, pasta, productos panificados en mezcla con otros pseudocereales y trigo sarraceno y bebidas con soya, los resultados revelan que la quinua es un sustrato rico en nutrientes para bacterias ácido lácticas, y que la fermentación genera cambios nutricionales, ya que se incrementan algunos macronutrientes y/o compuestos bioactivos, gracias al metabolismo de las bacterias y a su capacidad de hidrolizar almidón, también mejora las propiedades funcionales, tecnológicas y sensoriales debido a la modificación del almidón y a la producción de metabolitos. Lo que es una buena alternativa en el procesamiento de la quinua y en el desarrollo de alimentos funcionales.

Keywords:
Functional foods, pseudocereals, lactic acid bacteria.

Palabras clave:
Alimentos funcionales, pseudocereales, bacterias ácido lácticas.

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Ninguno declarado

Why was it conducted?

The review emerged from the need to acknowledge the nutritional potential of quinoa for the development of fermented products in the food industry. Stemming from technological surveillance enabling the analysis of the fermentation's impact on the nutritional, technological, and sensory properties of quinoa-derived products.

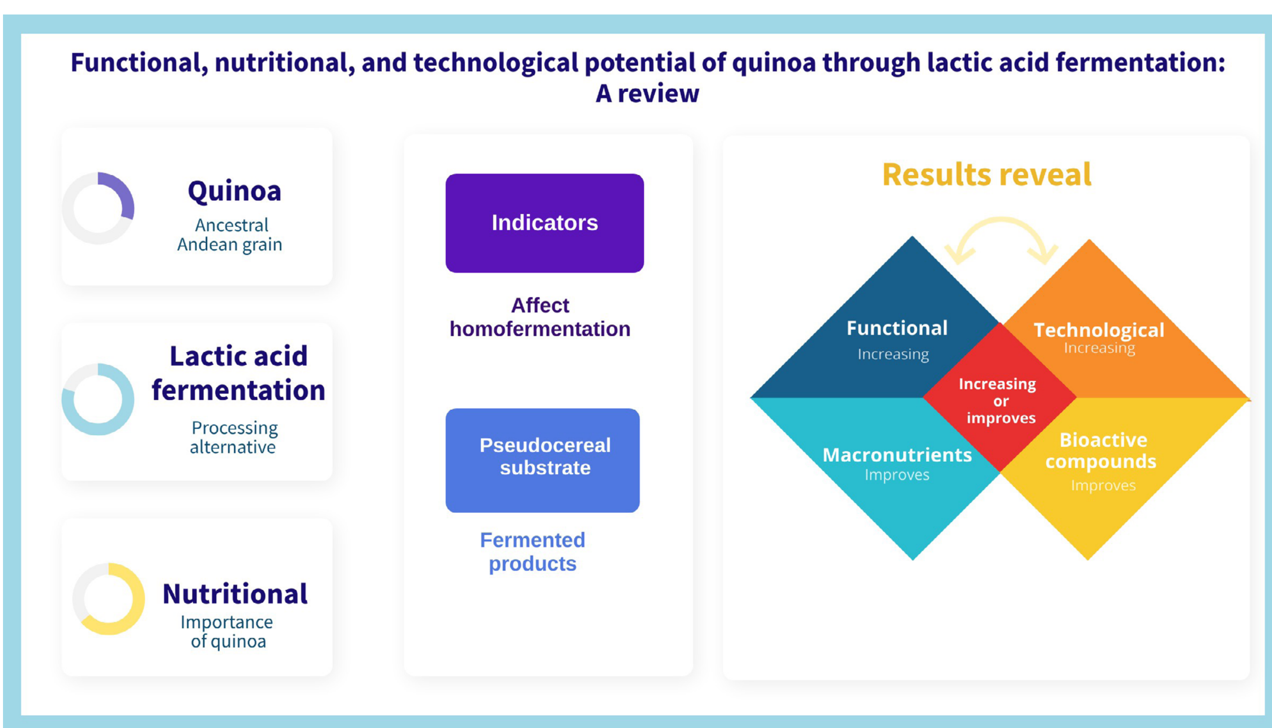
What were the most relevant outcomes?

Through the examination of various studies, it was found that fermentation enhances the production of bioactive peptides, an increase in total phenolic content, and greater antioxidant capacity. In fact, this biotechnological process can benefit the textural, nutritional, flavor, and aroma characteristics of developed products due to the production of a diverse range of metabolites and compounds such as organic acids and exopolysaccharides that contribute to the product.

What do these results contribute?

The results unveil the significance of quinoa in the development of fermented products with lactic acid bacteria as an alternative for the food industry in generating gluten-free, probiotic-rich, antioxidant-enriched, and lactose-free foods.

Graphical Abstract



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Introduction

Quinoa is an ancestral grain, native to countries in the Andean region (1) and it is currently being cultivated in other countries such as the United States, China, and France due to its importance in global food security. It is recognized for its resistance to different environmental conditions, biological diversity, nutritional potential, pest resistance, soil conservation, and its positive impact on the economy of local communities (1,2). Quinoa is a plant-based food known for its high protein content, excellent amino acid profile, essential fatty acids, lipids, fiber, vitamins, and minerals (3,4). When compared to other traditional cereals like wheat and rice, quinoa demonstrates superior nutritional content (5). The FAO and several studies highlight the nutritional potential of quinoa, particularly its ability to support lactic fermentations and the development of new products (6) thanks to its balance of essential amino acids, antioxidant content (flavonoids, polyphenols, and phytosterols), as well as its abundance of vitamins and minerals such as calcium and zinc (7). These characteristics have sparked research and innovation efforts in various fields focused on this versatile pseudocereal (8). Indeed, research and innovation efforts are evident in the cultivation of quinoa and grain, from different sectors according to the works reviewed in the Scopus database during the last 5 years, in the agricultural sector (36%), in biochemistry (9.1%), engineering (9.1%), and others to a lesser extent, mainly for crop improvement, development of new products, and evaluation of their functionality, demonstrating ample opportunities. In the field of new product development, research has been conducted on the fermentation process to enhance beneficial effects in sourdough bread-making (9) and quinoa-based beverages (10,11). It is evident that this pseudocereal can be explored and is susceptible to fermentation with lactic acid bacteria, to enhance organoleptic properties and encourage the development of gluten- and lactose-free foods (9–12), a viable alternative that improves nutritional and functional properties (3,13,14), providing added value to food preparations. Fermentation can generate bioactive peptides due to the balanced essential amino acid profile, increasing total phenolic content and antioxidant capacity (7,15,16).

Nutritional and functional properties of quinoa

Quinoa has high nutritional value due to its protein, mineral, vitamin, and carbohydrate content (17). It also contains bioactive compounds that are important components in the fermentation process. This pseudocereal has a high protein content, ranging from 12.9% to 16.5%, which is higher than some cereals (Oats: 11.6%, Rice: 7.5% and 9.1%, Corn: 10.2% and 13.4%, Wheat: 14.3% and 15.4%, Barley: 10.8% and 11%) (8,18). In terms of its essential amino acid composition, quinoa stands out for its high lysine content and a very complete amino acid profile (18,19). Most cereals are deficient in essential amino acids such as threonine, lysine, and tryptophan (20).Table 1 describes the amino acid profile of some pseudocereals, showing that quinoa has a high content of arginine (14.0 g/100 g of protein), proline (9.4 g/100 g of protein), and lysine (6.9 g/100 g of protein) compared to other pseudocereals. Furthermore, the lysine content exceeds the FAO/WHO recommended value (5.5 g/100 g of protein) (21,22). In fact, according to FAO recommendations, quinoa provides over 180% of the recommended daily intake of essential amino acids for adult nutrition (8). Its amino acid composition is considered balanced and capable of meeting human needs, and it is even comparable to the amino acid profile of milk (23). Quinoa protein is also digestible and biologically available (8,21,23).

Table 1. Composition of essential amino acids

Amino Acid	Quinoa	Kañiwa	Kiwicha	Amaranth
	(g/100 g crude protein)			
Val	4.6	4.2	3.8	5.1
Thr	3.9	3.3	3.3	4.5
Ser	4.9	3.9	5.0	5.6
Pro	9.4	3.2	3.4	4.8
Methionine	3.1	3.0	3.0	-
Phe+Tyr	8.2	-	-	6.6
Met+Cys	4.2	-	-	5.6
Lys	6.9	5.3	5.3	6.1
Leu	6.6	6.1	5.4	6.0
Ile	3.5	3.4	3.2	3.8
His	3.2	2.7	2.4	3.4
Gly	3.8	5.2	7.4	5.9
Glx	9.9	13.6	15.6	16.0
Asx	9.2	7.9	7.4	7.7
Arg	14.0	8.3	8.2	9.3
Ala	9.3	4.1	3.6	4.3
Try	-	0.9	1.1	-

Source: (21,24) Note: Not detected (-)

The starch content of quinoa ranges from 30 to 70% (25), with a low glycemic index generation and smaller granules. The fiber content (10%) is higher than that of some cereals, and it has a low FODMAP (fructose, fructans) content. Regarding lipid content, pseudocereals exhibit unsaturated fatty acids in higher percentages than some cereals, with lipid contents ranging from 2 to 10%, where 89.4% are unsaturated fatty acids, and 54.2 to 58.3% are polyunsaturated fatty acids (8). Vitamins are significantly higher in comparison to other typical cereals, meeting the population's vitamin needs, such as folate and vitamin B in their natural form. Quinoa is rich in phenolic compounds (flavonoids, polyphenols, and phytosterols) with high antioxidant potential (16). However, like all grains, including pseudocereals, quinoa contains antinutrients such as phytic acid, which reduces mineral availability. Other antinutritional components present in quinoa are saponins (8).

Lactic acid fermentation

Lactic acid bacteria are gram-positive, non-spore-forming microorganisms, deficient in cytochrome and catalase-negative, aerotolerant, acid-tolerant, and strictly fermentative, producing lactic acid as the primary end metabolic product of carbohydrate fermentation (26). Eleven genera have been recognized: *Carnobacterium, Enterococcus, Lactococcus, Lactobacillus, Lactosphaera, Leuconostoc, Oenococcus, Pediococcus, Streptococcus, Vagococcus*, and *Weissella.* These genera are divided into two groups: homofermentative and heterofermentative (27). In homofermentation, one molecule of glucose is converted into two molecules of lactic acid (28). In heterofermentation, lactic acid, carbon dioxide, and ethanol are produced in equal amounts. The genera *Pediococcus, Streptococcus, Lactococcus,* and *Vagococcus* are exclusively homofermentative, while *Lactobacillus* can be both homofermentative and heterofermentative. The other

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genera are all heterofermentative (27). The kinetics of the homofermentative process depend on the culture, substrate, nutritional and/or physicochemical characteristics of the matrix, and applied pre-treatments (29,30). Some studies report that lactic acid bacteria require fermentable carbohydrates, free amino acids, peptides, and vitamins for their growth (31). The basic indicators that should be evaluated in the process are shown in Figure 1.

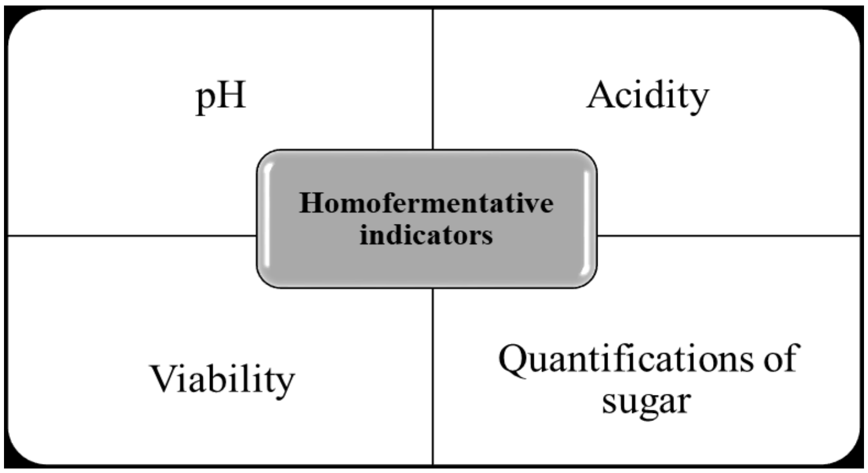

Figure 1. Homofermentative indicators

The intracellular pH of most microorganisms remains close to neutrality, but lactic acid fermenting bacteria can tolerate a low pH. However, only some can proliferate at pH values below 4.6 (28). These microorganisms can even decrease their growth rate, achieving a stable process, which is evident when there is a decrease in metabolic activity in terms of sugar consumption and acid production (32).
In lactic acid fermentation, there is an increase in acidity, but it depends on the substrate in the medium, fermentation time, and oxygenation. Various studies report that some strains can switch from homofermentative to mixed acid fermentation due to the composition of the medium (31). Regarding the functionality of probiotics, it is considered that these microorganisms can provide health benefits when present in high concentrations of 10^{8} to 10^{9} per gram of product, as long as these viable and available (33).

Substrate for lactic acid fermentation

Suitable raw materials as substrates for fermentation must have the required physical and chemical characteristics for the growth of microorganisms (34). An important compound is water content, as its availability will determine the growth of lactic acid bacteria. Salt or sugar influence water availability, and sugars allow for the production of organic acids, B vitamins, and amino acids. It is worth noting that in homofermentations, lactic acid bacteria derive energy solely from carbohydrate fermentation, requiring enzymes such as cellulases and amylases, among others (35).
Seeds have a high nutritional content necessary for germination and are primarily composed of carbohydrates, usually in the form of starch along with some free sugars. Seeds also contain minerals, vitamins, sterols, and other microbial growth factors, including lactic acid bacteria, which are selective and demanding. Therefore, seeds are suitable for fermentation if a prior treatment such as soaking or boiling in water is performed. Starch- and protein-rich seeds have been widely used to generate

fermented products by yeast and lactic acid bacteria. Furthermore, very few grains are consumed directly without undergoing any processing. Examples include rice, soybeans, corn, and other seeds that are often fermented to enhance their sensory acceptance (35,36). In countries like Asia and Africa, cereals are fermented and mixed with legumes to improve protein content. Additionally, grains naturally harbor microbiota that competes for nutrients (7).

Lactic acid bacteria (LAB) can adapt to different substrates, and quinoa can be a good alternative for fermentation (7,37,38). In fact, fermentation controls the growth of pathogens, and lactic acid bacteria act as bioconservatives due to the production of metabolites such as bacteriocins, which are antibacterial organic acids (3,7,22).

Fermentation of quinoa

In accordance with the consumer trend towards functional and gluten-free foods (6,39,40), numerous studies have been conducted to evaluate the nutritional composition, functionality, technological and sensory characteristics of fermented quinoa products. This process depends on various factors such as the grains used, strains, time, temperature, and pH (11,16)

As shown in table 2, fermented quinoa doughs have been evaluated with *Weissella cibaria, Weissella confusa, Leuconostoc spp.,* and *Lactobacillus plantarum* rich in exopolysaccharides (41). These microorganisms have been fermented in a mixed manner with *Lactobacillus plantarum* and yeasts (42), spontaneously by lactic acid bacteria and yeasts (43), with buckwheat and inoculated with *Lactobacillus paracasei* and *Pediococcus pentosaceus* (44) for use as technological improvers in bread development or to enhance the nutritional content of other gluten-free products. Some evaluated products include gluten-free bread with quinoa fermented by *Lactobacillus plantarum* (38) and by *Lactobacillus sanfranciscensis* (45), fermented quinoa beverages with *Lactobacillus plantarum, Lactobacillus acidophilus, Bifidobacterium sp., Bifidobacterium longum spp. infantis*, and *Streptococcus thermophilus* (16,46,47), fermented soy and quinoa extracts with *Lactobacillus casei* Bianchi et al., (50), muffins made with oat flour, corn starch, wheat flour, and quinoa sourdough inoculated with *Lactobacillus plantarum* (46), and fermented quinoa pasta with *Lactobacillus plantarum* (47).

Table 2. Studies on fermented quinoa

Fermentation Substrate	Strain	Results	References
Quinoa dough	*Strain C20: Lactobacillus plantarum* JCM1149 Strain JC5: *Lactobacillus plantarum* 1	The fermentation by LAB favored obtaining gluten-free baked products, higher nutritional content than traditional bread, improvements in the textural characteristics, reducing the hardness of the product for better consumer acceptance.	(48)

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Fermentation Substrate	Strain	Results	References
Quinoa flour	*lactobacillus plantarum* ATCC 8014	Fermentation quinoa flour leads to a sourdough nutritional enrichment and an improvement of its rheological features. The production of acids and the drop of the pH lead further to a bigger bioavailability of minerals, increasing their values at least twice.	(46)
Amaranth and Quinoa Flours	*Weissella cibaria and Lactobacillus plantarum*	The *W. cibaria* strain (C43-11), was able to produce a considerable amount of Exopolysaccharides (EPS) mainly in the presence of pseudocereals amaranth or quinoa and to hydrolyze proteins during fermentation.	(41)
Fermented quinoa beverages	*Bifidobacterium sp., Lactobacillus acidophilus, and Streptococcus thermophilus*	It was shown that the fermentation process significantly increased proteins and total phenolic content and antioxidation activity in the products. Sensory evaluation showed that the overall acceptability of quinoa-based fermented.	(49)
Extracts of quinoa and soy	*L. casei*	Potentially synbiotic beverage based on aqueous extracts of quinoa and soy with appropriate nutritional, rheological, and sensory characteristics.	(50)
Chia, quinoa and hemp seed flour	*Lactobacillus sanfranciscensis W2*	Increase of firmness and porosity in sourdough for gluten-free bread.	(45)
Red quinoa previously crushed	*Lactiplantibacillus plantarum CECT 220 , Bifidobacterium longum subsp. infants CECT 4551*	*in vitro* gastrointestinal digestion. High concentration levels of probiotics (10^6 – 10^8 CFU/ mL) in short fermentation periods (6h).	(16)

Fermentation Substrate	Strain	Results	References
Quinoa flour	*Lactobacillus plantarum 299v ® (Probi Mage, Sweden).*	Phytate reduction between 61.8% and 64.4%.	(51)
Quinoa	*Lactobacillus plantarum*	Significant increase in essential amino acids, free fatty acids,	(42)
Pasta made with quinoa sourdough	*Lactobacillus plantarum CRL 1964*	Increased bioavailability of vitamins (B_2 and B_9) and minerals (Calcium, iron and Magnesium)	(47)
Amaranth, buckwheat and quinoa flour	*lactic acid bacteria*	Gluten free sourdough	(43)
Cooked quinoa seeds.	*Lactobacillus paracasei A1 2.6 and Pediococcus pentosaceus GS.B.*	Increase in phenolic compounds (Flavonoids, Lignans , phenolic acids) and tyrosols .	(44)
Quinoa flour	*Lactic acid bacteria strains, previously isolated from quinoa: Lactobacillus plantarum, Lactobacillus rossiae, Pediococcus pentosaceus*	Lactic acid bacteria produced peptides with antioxidant activity and protein hydrolysis in fermented quinoa flour.	(13)

Effect of fermentation on the nutritional properties of quinoa products

Fermentation can lead to an increase in protein content and availability, as well as fatty acids. Quinoa has a high protein content (3,4). Table 2 shows that lactic acid fermentation allows for the development of gluten-free bread and pasta with high amino acid contents (9,47). Ceballos-González et al. (38) reported that fermentation of quinoa and wheat for the production of soft bread increased soluble protein content. In another study, the differences between protein hydrolysis and lipid production during quinoa fermentation with different strains were compared. Yeast, *L. plantarum,* and a combination of both for fermentation and found that different strains of microorganisms increase the protein hydrolysis index in quinoa. While yeast fermentation is more favorable for protein conversion in the pseudocereal, different types of fermentation improved the content of free fatty acids and increased functional lipids such as phospholipids. In fact, yeast is more favorable than *L. plantarum* in terms of improving the nutrition of fermented quinoa (42).

It is also possible to reduce and digest different antinutritional components of quinoa that cause food intolerance through fermentation (52). Ayub et al. (51), identified that fermentation of quinoa at 37°C with *L. plantarum* for the development of a beverage

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significantly reduced phytate concentration by 61.8% and 64.4% for two types of fermentation.

Probiotic microorganisms can remain viable in fermented quinoa beverages. In the study by Cerdá Bernad et al. (16), a fermented red quinoa beverage was developed, and fermentation allowed for the production of a beverage with high concentrations of functional microorganisms even after in vitro digestion. High levels of probiotics (10^6 to 10^8 CFU/mL) were found in short fermentation periods of quinoa inoculated with *Lactiplantibacillus plantarum* CECT 220 and *Bifidobacterium longum subsp. infantis* CECT 4551 after 6 hours, with high viability and functionality after gastrointestinal digestion. Several studies have demonstrated the effect of quinoa fermentation on the bioavailability and increase of antioxidants. For example, high concentrations of phenols have been reported (13,16,53), improved bioavailability of polyphenols (54), and increased antioxidant capacity in fermented quinoa beverages (16).
Furthermore, regarding vitamins, improvements in the concentration of water-soluble vitamins have been identified. High concentrations of vitamin B have been reported, and certain strains of lactic acid bacteria (*Lb. plantarum, Lactococcus rossiae, Lb. fermentum, Lactococcus buchneri, Lactococcus hilgardii,* and *Lb. brevis strains*) have a high capacity to produce vitamin B, including riboflavin (B2), folates (B9), and cobalamin (B12) (15,55). Fermentation also increases the availability of other micronutrients such as iron, zinc, and calcium (56).
Finally, an additional nutritional property is the production of exopolysaccharides, which can have a favorable effect on human health and help prevent various diseases (34). It is worth noting that strains of the Lactobacillus genus are recognized for their production of this compound (48).

Effect of Fermentation on Technological and Sensory Characteristics of Quinoa Products

Fermentation of quinoa for the development of bread, pasta, soups, and beverages can also improve organoleptic characteristics due to the development of favorable aromas (7). The modification of starch and proteins, influenced by organic acids produced during fermentation, favor textural properties such as dough firmness and starch viscosity (38). Jagelaviciute and Cizeikiene (45), in the development of quinoa, chia, and hemp seed bread with sourdough inoculated with *L. sanfranciscensis*, observed that although the volume of the bread was affected by the flours used, fermented quinoa bread achieved an acceptable porosity and a decrease in hardness compared to the non-fermented control. Consumer acceptance testing also showed that fermented quinoa bread increased the overall acceptability of the bread. Rizzello et al. (13) studied the production of bread with 20% fermented quinoa sourdough, primarily fermented by *L. plantarum*, and their results demonstrated a final volume and crumb cell area similar to the control, with a decrease in hardness.
Furthermore, fermented quinoa with *Lactobacillus spp.* produces exopolysaccharides (41,53), which are important for improving food qualities in terms of rheological and functional properties, acting as natural thickeners. According to Chis et al. (46), in the development of muffins using oat flour, corn starch, wheat flour, and quinoa sourdough with spontaneous fermentation, viscous properties increased due to the possible production of exopolysaccharides, but elasticity decreased.

Conclusions

It is widely recognized that quinoa is a food with high nutritional potential due to its protein, lipid, bioactive, and vitamin content. It is a plant matrix that can be utilized in the development of various products. The review found that quinoa is susceptible to fermentation, as the nutritional content of the substrate should be rich in free amino acids, vitamins, and peptides to promote the growth of lactic acid bacteria. However, it is important to highlight that lactic acid fermentation depends on various factors that can affect the process. For instance, if the pH of the substrate is below 4.6, it would hinder the growth of certain fermenting bacteria. Additionally, the time and temperature employed are also crucial factors.

Lactic acid fermentation of quinoa for product development can enhance nutritional properties by increasing amino acids, essential fatty acids, phenols, improving the bioavailability of polyphenols, and increasing B-complex vitamins. Furthermore, it results in the production of exopolysaccharides that can enhance the techno-functional properties of the products. Ultimately, it is concluded that fermenting quinoa, whether in its seed form or different products or by-products, offers nutritional, functional, and sensory advantages. This presents an opportunity for the industry and consumers who seek gluten-free, more nutritious products that meet desired sensory characteristics.

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