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Nutritional quality and nutrient bioaccessibility in sourdough bread

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Bread is a staple food in the human diet and a source of energy and nutrients for the body. The bakery process started with the homemade and artisanal way to produce bread leavened with sourdoughs started prepared from flour and water mixture. However, over the years, technological, microbiological, and nutritional aspects were studied to understand, industrialize, and select the micro-organisms involved in the bread fermentation to offer to the consumers' healthier bakery products. Therefore, this mini-review aims to describe the nutritional quality and the biotransformation observed in the flour during the fermentation process that impacts the nutrients bioaccessibility and the beneficial effects produced by this process to the final product and consumers healthy.

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Introduction

Bread is an ancient component in human fed and one of the more popular foods consumed worldwide [1]. This popular foodstuff was originally homemade; however, discovering the microorganisms responsible for the development of the dough and the development of food science and technology became possible to industrialize baking. Sourdough is an older natural yeast used in baking, which has been replaced by industrially produced yeast and chemical yeast agents over the years [2]. However, the natural fermentation process has been maintained over the years, especially nowadays, where consumers are more attentive to the nutritional quality of food and its impact on health.

The traditional sourdough comes from the mixture of flour and water, where flour's native lactic acid bacteria and yeasts produce the fermentation. The back-slopping process characterized by the use o small quantities of the product from the original fermentation as a starter culture in the next fermentation promotes the synthesis of organic acids, enzymes, antifungal compounds, exopolysaccharides and promotes proteolysis [3]. These compounds' formation and level in the sourdough depend on the raw materials' quality and the activity of the flour's natural microbiota or selected strains used to start the fermentation [4]. The search for the diversification of raw materials with an emphasis on their nutritional and functional properties has led to an interest in improving the sourdough fermentation process [5–7].

The nutrients and non-nutrient bioaccessibility and bioavailability are crucial to ensuring adequate nutrition to the fermentation medium and the final product's health benefits [4,8]. In this sense, sourdough can decrease the glycemic index of bread, improve the dietary fiber complex's properties, release bioactive peptides, and increase the absorption of minerals, vitamins, and phytochemicals. Also, the microbial metabolism of lactobacilli present in the dough produces new nutritionally active compounds, such as peptides and derivatives of amino acids (aminobutyric acid) with functionalities, as well as potentially prebiotic exopolysaccharides [4,9,10]. The by-products from microbial metabolism have aroused interest in the scientific community since it is possible to create new products focus on maintaining health in cases of chronic non-communicable diseases such as high cholesterol, cardiopathies, autoimmune diseases, irritable bowel syndrome, colitis, cancer, and diabetes [11,12•,13–15].

This short review reports the main biotransformations (Table 1) and the health benefits of the sourdough process, which increase the added value of the products regarding nutritional quality and nutrient bioaccessibility, and bioavailability.

Nutritional quality of sourdough bread

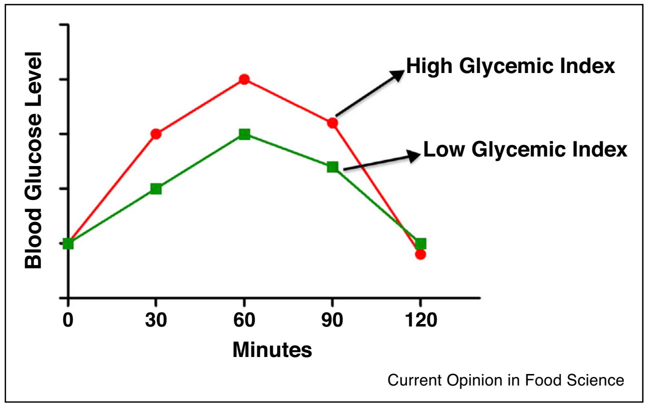
The quality of the yeast depends a lot on the type of grain used in the fermented dough; being the whole grain, the most recommended because it has more nutrients or substrate for the microbiota such as fibers, minerals, vitamins, and phytochemicals such as phenolic compounds, sterols, and tocopherols [4,16]. However, the type of grain and other ingredients that are added to the dough alter the final characteristics of the bread, like

Table 1

Summary of the main changes observed in bread produced by sourdough

Characteristics	Sourdough bread	Reference
Carbohydrates	↓ Glycemic index	[11,13,20]
	↓ Content of FODMAPS	[19•]
Protein	↑ Digestibility	[7]
	↑ Release of bioactive peptides	[7,12•,22,23,28,29]
	↓ Content of gluten	[10,26,27]
Minerals	↑ Bioaccessibility	[35]
Antinutritional factors	↓ Phytic acid	[30,31,34]
	↓ Acrylamide	[37–39]
Antioxidant activity	↑ ORAC	[36]

Figure 1



A representative glycemic response in order to intake low or high glycemic index foods.

technological, biochemical, and nutritional [5,6,17,18]. Also, the sourdough incubation process's temperature determines the type of predominant microbiota and its metabolites, which influences the autochthonous community's enzymatic activity and favors yeast fermentation processes and the dough acidification kinetics [19•].

Fermentation can modify the structure and composition of flours used to made bread; however, the cereals chemical composition has a great impact in the bread characteristics. Many modifications produced during the fermentation are very important to the quality of the final product. For example, wheat flour's chemical composition, the main ingredient in baking, shows the presence of fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAPS), a class of carbohydrates poorly digested that can be classified as a prebiotic. However, for some intestinal diseases, this group of carbohydrates can, directly and indirectly, contribute to the worsening of the intestinal' inflammatory status [11,19•]. Preliminary research has been showing that during the initial dough fermentation process, all FODMAPS are significantly reduced except for the polyols class (sorbitol and mannitol), with sucrose, fructose, and glucose being fully degraded in the first fermentation step and at the end of baking. It means that the natural fermentation could reduce at least 30% of the FODMAPS, which results in a sourdough bread with a lower amount of fermentable carbohydrates and free glucose [19•].

In addition to FODMAPS, the amount of starch and its digestibility are also important to control glycemic response and comorbidities. Bread is considered high-glycemic-index food; however, fermentation has been shown to decrease baking products' glycemic response (Figure 1). The dough's lower pH (below 3.5–4.0) favors the formation of resistant starch, reducing the starch digestibility and, consequently, the blood glucose level [11,13,20]. Siepmann *et al.* [21] observed hydrolysis of starch during the period to produce the mature fermented dough (stable microbial metabolism), with a quarter of the starch content being hydrolyzed on the first day of fermentation and on the third day, the lactic acid and yeast bacteria consumed almost all maltose, glucose and fructose released. The lactic acid bacteria use these carbohydrates as an energy source (glucose) and as a carbon source to homofermentative species and electron acceptors to regenerate cofactors to heterofermentative species (fructose) [19•]. The level of FODMADS decrease in the fermented mass is inversely proportional to the fermentation time.

Another pathway related to control glycemic response and sourdough bread intake is related to α-amylase inhibition. Diowksz *et al.* [12•] observed *in vitro* α-amylase inhibition in sourdough bread compared to control bread, indicating less starch degradation, which results in less glucose available to absorption.

There evidence in the literature about the increased protein digestibility in sourdough bread compared to bread made with baker's yeast due to the proteolysis during the fermentation period. Rizzello *et al.* [7] observed an increase of 16% in the sourdough bread digestibility compared to the bread made with baker's yeast (*Saccharomyces cerevisiae* E10) and an increase of 18.7% in the biological value of the protein. Proteolysis can release bioactive peptides and amino acids from the proteins' polymeric structure to be absorbed by the enterocytes. In agreement, the authors observed an increase in total free amino acids in volunteers' plasma that ate the sourdough bread, which maintains high and constant during all the tests (120 min) compared to the baker's yeast bread [7]. Also, Polese *et al.* [22] and Rizzello *et al.* [7] observed faster gastric emptying after consuming sourdough croissant and bread, suggesting that the appetite and satiety were regulated by bioactive peptides released from the products digestion instead of a mechanical effect. Additionally, Bondia-Pons *et al.* [23] observed an increase in small molecular weight peptides after *in vitro* hydrolysis of sourdough rye bread compared to commercial wheat bread and some metabolites associated with tryptophan that could be associated with low postprandial insulin response.

Another important change observed in proteins during the fermentation is the decrease content of gluten in sourdough bread. King *et al.* [24] showed in a systematic review and meta-analysis including 86 studies that celiac disease has a high incidence among females and children, and its prevalence has been increasing over the last decades, especially in the Western World. The exclusion of gluten sources from the diet is a dietary therapy used by people with celiac disease; however, this practice can limit food intake among these individuals. The main cereal used in the bakery is wheat, which shows in its composition gluten, a mixture of prolamin proteins rich in proline and glutamine amino acids. The sequences of amino acids in these proteins' structures release immunogenic peptides resistant to the human digestive enzymes associated with celiac disease [25]. Rashmi *et al.* [10] tested four *Bacillus* spp. (*Bacillus subtilis* GS 181 KX272352, *B. subtilis* GS 188 KX272353, *B. subtilis* GS 33 KX272356, *Bacillus cereus* GS 143 KX272357) isolated from wheat sourdough in four synthetic gliadin epitope (YPQ, QQP, PPF, and PFP) to evaluate its capability to reduce its immunogenicity through the tripeptides hydrolysis. The authors observed a reduction in the gluten's protein immunogenicity using sourdough fermented with these bacillus strains; however, they emphasize no total gluten removal [10]. Also, Di Cagno *et al.* [26] observed that lactic acid bacterias (*Lactobacillus alimentarius* 15M, *Lactobacillus brevis* 14G, and *Lactobacillus sanfranciscensis* 7A) in sourdough promoted more than 50% of gliadin hydrolysis without modifying the softness and stability of the dough during the fermentation. Although these results indicate that sourdough could promote changes in gluten proteins, Stefańska *et al.* [27] observed that lactic acid bacterias (53 diff ;erent strains) could not eliminate immunogenic epitopes (MW of 21 and 20 kDa) presents in the gliadin fraction.

Protein hydrolysis not only can decrease the immunogenicity of some protein sequences but also release some bioactive peptides. Diowksz *et al.* [12•] demonstrated *in vitro* the sourdough bread's ability to inhibit the angiotensin-converting enzyme (ACE). This enzyme is involved in converting angiotensin I into angiotensin II, which increases the aldosterone secretion that increases sodium reabsorption resulting in a rise in blood pressure. The authors observed 93% of ACE inhibition in bread before *in vitro* digestion and 59% after, indicating the hydrolysis of some bioactive peptides by digestive enzymes during the digestion process.

The biological responses can vary depending on the bioactive peptide released from the polymeric' protein structure. Rizzello *et al.* [28] observed the presence of lunasin, a peptide with chemopreventive property, in sourdough bread made with wholemeal wheat, soybean, barley, and amaranth flours. There are many mechanisms described to lunasin in cancer prevention, as well as anti-inflammatory action, antioxidant, and able to reduce the cholesterol [29]. This peptide was probably released during the protein hydrolysis in the fermentation step and maintained bioaccessible since it was detected in the water-soluble extracts prepared from the doughs [28]. The highest concentration of lunasin was identified in sourdough fermented with *L. brevis* AM7 and *Lactobacillus curvatus* SAL33 [28]. However, *in vivo* studies are necessary to elucidate this peptide's bioavailability since its biological effects depend on its stability during the gastrointestinal digestive process and absorption.

Flours may have antinutritional factors in their composition, decreasing the products' nutritional quality; however, these compounds may be reduced or extinguished during the fermentation process. Among the antinutritional compounds found in cereal and legumes flours are phytic acid, protein inhibitor, condensed tannins, raffinose, saponins, some of which are heat stable [30,31]. Methods such as germination, enzyme treatment, and fermentation are proposed to reduce these antinutritional factors in grains and seeds [32].

Decrease or removal of these antinutritional factors from the flour is important to secure the bioavailability of the minerals once it is decreased in the presence of phytic acid because of the negative electrical charge present in its structure, which complex with divalent cations such as Mg, Ca, Zn, Fe, Cu, and Mn, forming insoluble salts [33]. The stimulation of endogenous grain phytase and the phytase activity of the lactic acid bacteria and yeast by the pH decrease during the sourdough fermentation contribute to a decrease in phytate level in the bread [8,30]. Fekri *et al.* [30] demonstrated that some yeast (*Kluyveromyces marxianus*, *Kluyveromyces lactis*, and *Kluyveromyces aestuarri*) and bacterias (*Enterococcus faecium*, *Pedostiococcus*, and *Leuconostoc citreum* strain) presents in the sourdough microbiota have phytase activity and resistant to low pH and bile action. However, *K. marxianus* has a higher phytase activity than *S. cerevisiae* and the lowest phytic acid content compared to whole wheat flour [30]. Additionally, Yildirim and Arici [31] observed among the lactic acid bacteria isolated from sourdough highest phytase activity and phytic acid degradation to *L. brevis* HEB33 and *Lactobacillus plantarum* ELB78.

Rodrigues-Ramiro *et al.* [34] comparing three baking processes observed completed phytic acid degradation and increased at eightfold in iron bioaccessibility in wholemeal sourdough bread compared to Chorleywood and traditional bread. In the same way, Leenhardt *et al.* [35] observed an increased level of soluble magnesium in sourdough compared with the control, which could be explained by reducing phytic acid content or even the dough pH decreasing during the fermentation.

Changes in phenolic compounds present in the flour are also observed after the fermentation. Di Nunzio *et al.* [36] showed using different types of flour (wheat, wheat wholemeal, spelt, and rice) increased the level of free phenolic acids and antioxidant activity (ORAC) in the sourdough bread compared with flours. It is important to emphasize that the authors observed differences among the flours, which could be explained by the biotransformation of the compounds released from the matrix or degradation during the baking process.

Finally, Nachi *et al.* [37] observed a reduction in acrylamide formation in sourdough bread using four lactic acid bacteria (*L. brevis* strain S12, *L. plantarum* strain S28, *Pediococcus pentoseus* strain S14, and *Pediococcus acidilactici* strain S16). Acrylamide is a carcinogenic compound formed by the Maillard reaction during the baking process; however, the low pH produced during the fermentation appears to be a protective parameter to prevent the Schiff base's formation in the acrylamide synthesis pathway [38]. Nasiri Esfahani *et al.* [39] compared the effect of using different *Lactobacillus* strains (*L. plantarum* PTCC 1896, *Lactobacillus sakei* DSM 20,017, *Lactobacillus rhamnosus* DSM 20,021, and *Lactobacillus delbrueckii* DSM 20,081) with yeast (*S. cerevisiae*) in reducing-acrylamide content in whole-wheat sourdough bread. The authors observed decreased acrylamide content in all sourdough bread prepared by combining different lactobacillus strains and the commercial yeast compared to bread made with yeast. There are many mechanisms involved in this acrylamide content reduction, among them the positive correlation between the acrylamide content and the dough pH. In addition, the authors noted that the potential for reducing the acrylamide content of lactobacilli was strain-specific, with the best results observed for *L. plantarum*, *L. sakei* subsp. *sakei* and *L. rhamnosus* [39].

The use of genomics has been an ally in the identification of the most favorable microbiota for each sourdough matrix and specific objectives such as the production of lyophilized starters or even the isolation of microorganisms of interest in health [37,38].

Health effects of sourdough

Food intake and food choices can modulate health status and prevent disease development. Zanfardino *et al.* [40•] observed the effects of a traditional recipe for Neapolitan pizza Margherita (long period of fermentation) in the glycemic response of children and teenagers with Type 1 diabetes compared to a short period of dough fermentation. The participants administered an insulin bolus 15 min before the meal, determined by the bolus calculator, and the glycemic response of the individuals was monitored for 11 hours after the meal intake. The authors observed more glycemic control when the individuals consumed the pizza prepared using a long dough fermentation period, with less time in hypo or hyperglycemia than the pizza prepared with a short period of fermentation. These results can be associated with the lower content of monosaccharides and oligosaccharides in the long-period fermentation dough. Although there are some limitations in the study, it was possible to demonstrate the beneficial effects, especially in carbohydrate metabolism, to consume baking products made from a long period of fermentation [40•].

Traditionally, sourdough's bread main ingredient is wheat flour; however, wheat can be replaced for different kinds of conventional or non-conventional flours (rye, barley, quinoa, triticale, sorghum, oat, and maize) to improve the quality of the bread and to attend the consumer expectance and necessities. The use of non-conventional flours to make sourdough can improve the beneficial health effects associated with the bakery products. Coda *et al.* [41] observed that the combination of chickpea, amaranth, buckwheat, and quinoa mixed flour produced ten times more γ-aminobutyric acid (GABA) than traditional wheat flour sourdough. GABA is a non-protein amino acid that acts as an inhibitory neurotransmitter in the central nervous system, having several protective effects in the body such as controlling hypertension, hyperglycemia, inflammation, degeneration of target tissues, and acting as an antioxidant [42].

FODMAPS are associated with the symptoms associated with irritable bowel syndrome (IBS), leading to the exclusion of wheat products from these individuals' diet. There is a hypothesis that intestinal dysbiosis could exacerbate IBS symptoms; however, the consumption of food able to regulate the microbiota could decrease these symptoms. The effect of sourdough intake in the gut microbiota was tested *in vitro* using a fecal sample from healthy and IBS donors [43]. Increases in fecal bifidobacteria, a gender less associated with IBS symptoms, were observed in the feces of healthy individuals incubated with sourdough bread compared to samples prepared with commercial yeast or without fermentation time. Although no effect on bifidobacteria was observed in fecal samples from donors with IBS; the fermented dough bread showed less gas production and less number of sulfate-reducing bacteria in IBS patients, showing that long fermentation may be an alternative for the production of bread for patients with this syndrome [43].

Also, Abbondio *et al.* [44•] observed a change in gut microbiota taxonomy and the metabolic functions in rats fed with a diet supplemented with sourdough bread compared to the bakery's yeast bread. The consumption of a diet supplemented with sourdough bread led to a reduction of specific members in the *Alistipes*, *Mucispirillum*, and *Mycoplasma* genera, as well as a higher abundance of asparaginases expressed by *Bacteroides*. These results indicate a positive effect of sourdough bread intake to prevent the development of obesity and colon cancer, among other non-communicable diseases.

Conclusions

Consumer awareness and interest in the quality of food and nutrition has grown over the past decade. Likewise, several studies have demonstrated the effects of sourdough on the technological and nutritional qualities of bread. The use of non-conventional alternative flours is another alternative to adding value to sourdough bread, allowing gluten-free bread production. Bioactive compounds released from the matrix and the increased bioaccessibility of nutrients and non-nutrients contribute to the health benefits from the consumption of sourdough bread. However, some *in vivo* and clinical trials are needed to expand knowledge of bioavailability and the molecular pathways involved in the biological effects associated with sourdough bread intake.

Conflict of interest statement

Nothing declared.

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This study has new insight into the effect of sourdough intake in the gut microbiota and its possible relationship with its biological health effects.