Chapter 9
Nutritional Aspects of Cereal Fermentation with Lactic Acid Bacteria and Yeast

Kati Katina and Kaisa Poutanen

9.1 Introduction

Sourdough fermentation is best known and most studied for its effects on the sensory quality and shelf life of baked goods. Acidification, activation of enzymes and their effects on the cereal matrix as well as production of microbial metabolites all produce changes in the dough and bread matrix that also influence the nutritional quality of the products. The nutritional quality is formed through the chemical composition and structure of the fermented foods, i.e. content and bioavailability of nutrients and non-nutrients. Sourdough fermentation can change all of these, as previously reviewed by Poutanen et al. [1] and Katina et al. [2].

Sourdough fermentation has been traditionally applied to whole grain foods, and it is a good means of making whole grain bread more palatable. Rye bread is an extreme example of this, as most of the whole-grain rye bread is made through sourdough fermentation [3]. Sourdough fermentation, also in the form of pre-treating raw materials, is again gaining interest also in mixed flour and dietary-fibre-enriched baking [4], where it also can change the properties of the dietary fibre complex. Fermentation has been studied for reducing the glycaemic response of bread [5, 6], and for increasing the uptake of minerals [7]. Microbial metabolism during sourdough fermentation may also produce new nutritionally active compounds, such as vitamins [8] and potentially prebiotic exopolysaccharides [9].

This chapter will deal with nutritionally relevant changes in cereal starch, protein, dietary fibre, vitamins, minerals and some phytochemicals, and discuss the potential of microorganisms to produce new compounds.

K. Katina (✉) • K. Poutanen
VTT Technical Research Centre of Finland,
PB 1000, 02044 VTT Espoo, Finland
e-mail: kati.katina@vtt.fl

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9.2 Effects on Cereal Biopolymers

9.2.1 Starch

Dietary carbohydrate is the major source of plasma glucose. An increase in the amount of rapidly digestible carbohydrate in the diet causes a rapid increase in blood glucose levels and a large demand for insulin in the postprandial period. The major carbohydrate sources in the Western diet contain rapidly digestible starch, and many common starchy foods like bakery goods, breakfast cereals, potato products and snacks produce high glycaemic responses. There are strong indications that the large amounts of rapidly available glucose derived from starch and free sugars in the modern diet [foods with high glycaemic index (GI) and high insulin index (II)] lead to periodic elevated plasma glucose and insulin concentrations that may be a risk factor to health [10].

Most processed starchy foods have low to medium moisture contents, thus their digestion is basically a solid–liquid two phase reaction, and the enzyme (particularly α-amylase) needs first to diffuse into the hydrated solid food matrix, bind to the substrate, and then cleave the glycosidic linkages of the starch molecules [11]. Factors affecting the binding of α-amylase to substrates [e.g. inhibition by the hydrolysis products (maltose and maltotriose)] will slow down the enzymatic reaction and thus digestion of starch. Other physiological factors affecting starch digestibility include gastric emptying, enzyme inhibitors and viscosity in the digestive tract [12].

Macro- and microstructure of cereal foods has a profound influence on the digestibility of starch, as reviewed by Singh et al. [13]. Especially, the characteristics of starch per se are of crucial importance for glucose response. Amylose-rich starches are more resistant to amylolysis than waxy or normal starches. The major intrinsic factors affecting raw starch digestibility include the supramolecular structure (packing of crystallites inside the starch granule), the ratio of amylase and amylopectin, the amylopectin fine structure, and the surface characteristics of starch granules [14]. In vitro, native starches are hydrolysed very slowly, and to a limited extent, by amylases [15–17]. When starch is used in food processing, starch gelatinisation, i.e. the process of disrupting starch crystalline structure with heat and moisture, usually results in a decrease or loss of the slow digestion property of native cereal starches [18]. Gelatinised starch will exist for example in bakery products in a partially or completely amorphous state. Thus, the more gelatinised starch is, the more rapidly it will be digested [19]. In many common starchy foods, such as in regular white wheat bread, the starch is highly gelatinised and product structure very porous, resulting in rapid degradation of starch in the small intestine and a very rapid rise of blood glucose level (high GI).

There are several mechanisms leading to slow digestion of gelatinised starch [20]. The first group of important factors is related to the state of starch in the food matrix. Starch retrogradation, which is the reassociation of amylose and amylopectin to form double helices and possible crystalline structures, promotes slow

digestibility. The molecular structure of amylopectin is also an important factor, as high branch density has been shown to be linked to slow digestibility. Lowering the degree of starch gelatinisation and partially retaining the A-type crystalline structure of related starches is one effective way to increase the content of slowly digestible starch in food products. The second group of factors include impact of chewing on food structure, gastric emptying rate, transit time in the small intestine and the properties of digestive enzymes [16].

The means to slower starch digestibility in wheat flour-based products such as bread, biscuits and breakfast cereals are rare, if the addition of a high amount of intact kernels is excluded due to the resulting inferior product quality and consumer preferences. For wheat bread, the use of pre-fermentation technology (sourdough) or the addition of soluble fibres were identified in a recent review as the only suggested means to reduce GI [21].

The fermentation of the wheat and rye flour matrix with lactic acid bacteria (sourdough process) has been shown to lower GI of wholemeal barley bread [19, 22] and wheat bread [5, 23–25], and insulin index (II) of rye breads with varying dietary fibre (DF) content [26]. Several mechanisms have been proposed to be involved in sourdough processing contributing to reduced starch digestibility. Formation of organic acids, especially lactic acid, during fermentation has been suggested to be a main reason. The physiological mechanisms for the acute effects of acids appear to vary. Whereas lactic acid lowers the rate of starch digestion in bread [22], acetic and propionic acids appear instead to prolong the gastric emptying rate [27]. Chemical changes taking place during sourdough fermentation have been postulated to diminish the degree of starch gelatinisation [19], which would partly explain the lower digestibility of sourdough-fermented cereal foods. Sourdough fermentation has been also shown to promote the formation of resistant starch, which has slower digestibility [28].

At the product level, tissue integrity, porosity and structure of starch are important characteristics influencing glycaemic response. Rye breads baked from wholemeal or white rye flour with very different fibre contents produced lower insulin responses than white wheat bread, when the food portion size was standardised to provide 50 g of starch [26]. The breads were baked with a sourdough process and with 40% of a total amount of rye flour being pre-fermented before incorporation into the dough. The results suggested that with all rye breads, regardless of bran content, less insulin was needed to regulate blood sugar from the same amount of starch in comparison to normal wheat bread. The influence is probably due to the more rigid and less porous structure of rye bread, and because of the presence of organic acid formed during sourdough fermentation [29].

There also may be other mechanisms for the sourdough to regulate GI/II of the products. For example, pH-dependent proteolysis generally occurs during sourdough fermentation [30] producing significant amounts of peptides and amino acids in the sourdough. These may have a role in regulating glucose metabolism [31]. Furthermore, the results of Katina et al. [32] demonstrate that sourdough fermentation increases the amount of free phenolic compounds, which may also have an impact on lowering the GI/II [6, 33].

However, not all the sourdough breads automatically have low GI/II [34]. In general, a rather low pH of sourdough and subsequent bread is required to obtain lowered GI or II; typical values being 3.5–4 for sourdoughs and 3.8–5.1 for sourdough breads [5, 24, 25, 35, 36]. The efficacy of individual acids reducing GI is not completely clarified [6], and may vary between different bread types. In addition, such a low pH will in many cases reduce bread volume and increase density, which have been shown to promote low GI per se also in regular wheat breads [37]. Furthermore, the sensory quality of highly acidic breads may be a limiting factor for consumer acceptability of such breads, and means for enhancing the efficacy of fermentation while maintaining higher pH levels would be desirable. Further studies will be needed to clarify the direct influence of sourdough metabolites (acids, peptides, and exopolysaccharides) on starch digestibility, and the indirect impact of sourdough fermentation on cereal matrix properties (density, liberation of phenolic compounds, state of protein, and formation of resistant starch), which all influence digestibility.

9.2.2 Protein

Protein degradation that occurs during sourdough fermentation is among the key phenomena that affect the overall quality of sourdough bread as reviewed by Gänzle et al. [30]. Proteolysis by sourdough fermentation has been found to be higher than in just yeasted doughs. During dough fermentation, the proteolysis by LAB releases small peptides and free amino acids, which are important for rapid microbial growth and acidification and as precursors for the flavour development of leavened baked products [38]. Furthermore, this proteolytic activity might be used as a tool to reduce certain allergen compounds. Cereal proteins are one of the most frequent causes of food allergies. Wheat proteins may induce a classical allergy affecting the skin, gut or respiratory tract, exercise-induced anaphylaxis, occupational rhinitis or asthma [36, 39], and protein modification with fermentation offers possibilities to reduce their allergy-causing properties. For example, De Angelis et al. [36] demonstrated the capacity of probiotic VSL#3 to hydrolyse wheat flour allergens. Albumins, globulins, and gliadins extracted from wheat flour, a chemically acidified and started doughs, and total proteins extracted from breads were analysed by immunoblotting with pooled sera from patients with an allergy to wheat. Several IgE-binding proteins persisted after treatment of baker's yeast bread with pepsin and pancreatin. The signal of all these IgE-binding proteins disappeared after further treatment by VSL#3. Utilisation of the VSL#3 strain as a starter for bread making, caused a marked degradation of wheat proteins, including some IgE-binding proteins. De Angelis et al. [36] showed that the IgE-binding profile of the bread manufactured by VSL#3 was largely different from that of baker's yeast bread. The IgE-binding proteins that persisted in the bread made with VSL#3 were completely degraded by pepsin and pancreatin.

Intensive degradation of prolamin of wheat and rye has also opened new possibilities to use these cereals even as part of gluten-free diets [23, 40, 41]. Controlled proteolysis in wheat and rye doughs was suggested to reduce gluten levels to such an extent that the products were tolerated by celiac patients [42]. While such sourdoughs with extended fermentation time are not suitable for bread production as such, they can be incorporated as baking improvers into gluten-free recipes. It was shown in a 60-day clinical trial that biscuits and cakes produced using a hydrolysed wheat product made using sourdough lactobacilli and fungal proteases were not toxic to patients with celiac disease [43].

The quality of gluten-free bread is often inferior when compared to conventional (wheat) products [2]. However, by degrading prolamins of wheat or rye with a proteolysis-intensive sourdough process, it is possible to produce good quality gluten-free bread with sourdough technology [40, 42]. The concept of complete elimination of gluten, however, is controversial. Gluten is considered essential for wheat baking and the complete elimination of gluten from wheat and rye, albeit possible, is technically challenging in industrial baking operations. The use of germinated rye in sourdoughs may avoid, in part, such controversy because the water binding as well as gas retention in rye doughs are mediated by pentosans which remain unaffected by proteolysis [30]. De Angelis et al. [23] demonstrated that fermentation by selected sourdough lactic acid bacteria to decrease celiac intolerance to rye flour [44, 45] used flour from germinated wheat and rye grains to enhance the proteolysis and efficient degradation of wheat and rye prolamins.

Recently, it has been demonstrated that sourdough fermentation can promote the formation of bioactive peptides [46–48]. Bioactive peptides are defined as specific protein fragments that have positive effects on body functions or conditions and that may influence human health. Usually, bioactive peptides correspond to specific sequences from native proteins, which are released through hydrolysis by digestive, microbial, and plant proteolytic enzymes, and their levels generally increase during food fermentation. Coda et al. [46] summarised that bioactive peptides, on the basis of in vitro and in vivo studies, have demonstrated a large spectrum of biological functions, such as opioid-like, mineral-binding, immunomodulatory, antimicrobial, antioxidative, antithrombotic, hypocholesterolemic, and antihypertensive activities. The ability of selected lactic acid bacteria to produce antioxidant peptides during sourdough fermentation by using various cereal flours as substrates was demonstrated [46]. The radical-scavenging activity of water/salt-soluble extracts (WSE) from sourdoughs was shown to be significantly ($P < 0.05$) higher than that of chemically acidified doughs. Twenty-five peptides of 8–57 amino acid residues were identified in their study and nearly all sequences shared compositional features that are typical of antioxidant peptides. All of the purified fractions showed ex vivo antioxidant activity on mouse fibroblasts artificially subjected to oxidative stress. Recently, interest in antioxidant peptides derived from food proteins has increased, and evidence that bioactive peptides prevent oxidative stresses associated with numerous degenerative aging diseases (e.g. cancer and arteriosclerosis) is accumulating [49].

Rizzello et al. [47] exploited the potential of sourdough lactic acid bacteria to release lunasin, an anticarcinogenic peptide, during fermentation of cereal and

non-conventional flours. They used selected lactic acid bacteria as sourdough starters to ferment wholemeal wheat, soybean, barley, amaranth, and rye flours. Sourdough-originated lunasin was identified in their study and the concentration of lunasin was shown to increase up to two to four times during fermentation.

From a practical standpoint, baked cereal goods are currently manufactured by highly accelerated processes. Long-term fermentations by sourdough, characterised by a cocktail of acidifying and proteolytic LAB and yeasts, have been almost totally replaced by the indiscriminate use of chemical and/or baker's yeast leavening agents. In these technological circumstances, cereal components (e.g. proteins) are subjected to very mild or no degradation during manufacture, resulting in less easily digestible foods compared to traditional and ancient sourdough baked goods [41].

9.2.3 Dietary Fibre

Dietary fibre consists of the plant polysaccharides and lignin that are resistant to hydrolysis by the digestive enzymes of man. A high consumption of dietary fibre may lower the risk of cardiovascular disease, diabetes, hypertension, obesity, and gastrointestinal disorders [50, 51]. Cereal foods are an important source of dietary fibre, and because of their role as a staple food provide an important food group to increase the currently too low intake of dietary fibre. Sourdough fermentation provides two main options for enhancing utilisation of fibre-enriched products: (1) It is important technology in the manufacture of whole grain bread, especially rye bread, and (2) it may be used to modify fibre-rich cereal ingredients such as bran and germ for improved technological functionality.

Wholemeal rye and wheat are very good sources of dietary fibre. However, a high content of fibre poses technological challenges for baking. For whole-grain rye baking, sourdough fermentation is an essential part of the process [2]. Without sourdough wholemeal rye or wheat-rye flour mixes are very difficult to process, and sourdough improves the overall quality and shelf life of whole-grain rye breads. The rye sourdough process not only improves flavour and texture of rye bread but enables consumption of wholemeal rye, which is well known for its high nutritional quality and health-promoting properties.

Bran sourdough (or bran pre-ferment) is a potential means to improve the quality of high fibre bread [4, 52–54]. The use of bran sourdough improves loaf volume and crumb softness of high-fibre wheat breads [4, 52, 55] and bread with 10-% fermented bran has been reported to provide the best sensory properties of bread [53]. The impact of fermentation is assumed to be related to control of endogenous microbiota of bran, endogenous xylanase activity and subsequent solubilisation of arabinoxylans in bran fermentation [4]. Enzyme activity and gluten characteristics of dough containing fermented bran will be modified by the acidity produced during fermentation, and subsequently decreased pH. The fibre content of the bran does not change significantly in a short fermentation time but can decrease slightly during prolonged fermentation due to hydrolysis of cell wall structures (Katina, unpublished data).

Use of enzymes (α-amylase, xylanase, lipase) in combination with yeast fermentation of bran has been shown to increase the volume of the subsequent bread, and soften its texture significantly [55]. Use of fermented bran improves carbon dioxide retention of the dough, and the use of enzymes strengthens that effect. Also, addition of insoluble arabinoxylans and xylanase enzymes has been shown to increase the volume of the sour dough bread [56]. Arabinoxylans function as the source material of xylose and arabinose, which accelerate the acidification rate and positively interfere with the metabolism of sourdough microflora.

Sourdough fermentation improves the technological functionality of bran as a baking ingredient, but it most probably also changes the quality of dietary fibre. The physiological effects of dietary fibre depend on the chemical but also physical characteristics, including degree of polymerisation of the polysaccharides, presence of side chains and degree of cross-linking, particle size and cell wall integrity [51]. Because of solubilisation of arabinoxylan, sourdough fermentation may influence its fermentation pattern and also produce prebiotic oligosaccharides [57]. It may also influence the bioaccessibility of phytochemicals associated with the dietary fibre complex, as shown below.

Wheat germ, in addition to vitamins and lipids, contains a significant amount of dietary fibre. Fermentation of wheat germ has recently been noticed to enhance the volume of the bread and decrease the rate of firmness [58]. The use of wheat germ as a source of dietary fibre for bread is still moderate because of its poor shelf-life stability. The high lipase and lipoxygenase activities cause sensitivity to oxidation which leads to the release of free fatty acids and, consequently, to the appearance of rancidity in baked goods. Sourdough fermentation stabilised and enhanced some nutritional and chemical properties of the wheat germ. Because of lactic acidification, the lipase activity of the sourdough fermented wheat germ has been shown to be lower than that found in the raw wheat germ [58].

9.3 Micronutrients

9.3.1 Vitamins

Whole-grain cereal foods are an important source of vitamins, such as thiamine, vitamin E and folates. Yeast fermentation increases the folate content during the pre-fermentation process of both wheat flour and bran [32, 59] and rye [32, 59, 60], causing over a doubling of folate in rye fermentation [60]. The presence of yeast has been shown to be a crucial factor for increased folate production in rye sourdough as sourdough bacteria had only slight effects on the synthesis of folates [61]. Yeast strains have been shown to be different in their capability to produce folate, and thus a high folate-producing strain could be used as an alternative to folate fortification [62, 63]. The folate content in fermented cereal foods can be further increased by the use of malted or germinated grains, as reviewed by Jagerstad et al. [64]. Conversely, 25–38% reduction of folate content in yeast and LAB fermented breads have been reported by Gujska et al. [65].

Thiamine content has been reported to increase especially in elongated yeast fermentation [8, 66], but also to decrease in the actual baking process [67]. Prolonged yeast or sourdough fermentation maintained the original content of vitamin B_1 in whole wheat baking in contradiction to a short process, which reduced its amount. Whole wheat breadmaking with yeast (from kneading to final bread), with long fermentations time resulted in a 30% enrichment in riboflavin. The fermentation step can thus improve the retention of vitamins in the baking process. The use of both yeast and sourdough did not have a synergistic effect on B-vitamin levels [8]. Production of the B_2 vitamin with strain selection for enrichment of pasta and bread has also been recently demonstrated by Capozzi et al. [68]. The applied approaches resulted in a considerable increase of vitamin B_2 content (about two- and threefold increases in pasta and bread, respectively), thus representing a convenient and efficient food-grade biotechnological application for the production of vitamin B_2-enriched bread and pasta. This methodology may be extended to a wide range of cereal-based foods, feed, and beverages. However, sourdough or yeast fermentation do not automatically increase the levels of all vitamins; decreased levels have been observed for vitamin E during sourdough preparation and dough making [69], and for levels of tocopherol and tocotrienol in rye sourdough baking [60].

9.3.2 Minerals

Whole grains are a good source of minerals, including calcium, potassium, magnesium, iron, zinc and phosphorus. As the bran fraction of the grain also contains phytate (myo-inositol hexaphosphate), the bioavailability of minerals may be limited. This has a large impact especially in developing countries, where iron deficiency is a common nutritional disorder, especially among children and women. Grains contain 3–22-mg phytic acid per gram [70], concentrated in the aleurone layers. Phytate has strong chelating capacity and forms insoluble complexes with dietary cations, thus impairing mineral absorption. Phytases are able to dephosphorylate phytate, forming free inorganic phosphate and inositol phosphate esters, which have less capacity to influence mineral solubility and bioavailability. It has been shown that iron was more bioavailable in mice when fed in sourdough bread vs. straight dough bread [71], and absorption of zinc, magnesium, and iron was higher in rats when bread was baked using sourdough [72].

Grain endogenous phytase activity is accelerated in the acidic environment produced in sourdough fermentation. Lactic acid bacteria and yeasts may also possess some phytase activity. The pH optimum of wheat phytase is pH 5.0, and that of yeast is somewhat lower, i.e. pH 3.5 [73]. A moderate decrease of pH to 5.5 in fermentation reduces phytate content of whole wheat flour by 70% due to enhanced action of endogenous phytase present in the flour [74]. It was suggested that the endogenous flour phytase activity was much more influential than the microbial phytase of the sourdough. No major phytase activity was found in screening of 50 lactic acid bacteria strains isolated from sourdoughs [75], even though in studies

with phytic acid as the only carbon source sourdough-originated lactic acid bacteria have been reported to utilise it [76, 77]. Phytase activity has been detected in commercial baker's yeasts [78], and variable activities were detected in traditional sourdough starters containing both yeast and lactic acid bacteria [79, 80]. Yeast strains high in phytase activity have also been suggested to be potential phytase carriers in the gastrointestinal tract [81].

Phytase action is dependent on the fermentation conditions: flour particle size, acidity, temperature, time and water content [82, 83]. Sourdough fermentation has been shown to be more effective in solubilising minerals in whole-wheat flours than its bran fraction. Bran particle size influenced calcium and iron solubilisation, which only happened if the bran was finely milled [7]. Pre-fermentation of bran with lactic acid bacteria increased phytate breakdown (up to 90%) and increased magnesium and phosphorus solubility [84].

Selenium-enriched rye and wheat seeds have been used to produce fermented sourdough bread, and studied in human volunteers for bioavailability of selenium [85, 86]. The selenium enrichment was made by incubating the seeds in selenium solution. The high content of selenium in raw material was reflected in high contents in the sourdough bread and further in humans having consumed the bread.

9.3.3 Phytochemicals

Phytochemicals are biologically active compounds in the cereal grain and they have been suggested to be among the factors contributing to the protective properties of whole grain foods [87]. The outer layers of grains, such as bran, contain much higher levels of phytochemicals, such as phenolic acids, alkylresorcinols, lignans, phytosterols, tocols and folate, than the inner parts [60, 88]. Processing may decrease or increase the levels, and also modify the bioavailability of these compounds as reviewed by Slavin et al. [89], and for the phenolic compounds of rye as reviewed by Bondia-Pons et al. [90].

Wheat bread containing a sourdough-fermented wheat bran-flour mixture was recently shown to provide higher antioxidant potential as compared to regular wheat bread [91]. Traditional rye sourdough has been shown to increase the antioxidant activity (DPPH radical scavenging activity) in the methanol-extracted fraction of rye sourdough, concurrently with increased levels of easily extractable phenolic compounds [60]. Accordingly, the antioxidant capacity of traditional rye breads baked with sourdough has been shown to be higher than that of common white wheat bread, the highest values reported for breads made with whole meal flour [67, 92].

Fermentation of rye or wheat bran with yeast and especially with added cell wall-degrading enzymes was able to increase the level of free ferulic acid [4, 32, 93]. Ferulic acid is a structural component in cell walls, cross-linked to arabinoxylan. Since most of the ferulic acid is covalently bound to the cell wall structures, its bioaccessibility in physiological conditions is low, and bioprocessing can be used as

an effective means to increase the bioaccessibility of ferulic acid. Wheat bread supplemented with bioprocessed bran increased the in vitro and in vivo bioaccessibility of phenolic compounds as well as the colonic end metabolite 3-phenylpropionic in breads, and exerted anti-inflammatory effects ex-vivo [93, 94].

9.4 Microbial Exopolysaccharides

Dietary non-digestible oligosaccharides (NDO) have been shown to modulate the composition and activity of intestinal microbiota, and they may also exert health benefits in humans by improving bowel function, prevention of overgrowth of pathogenic bacteria through selective stimulation of non-pathogenic members of intestinal microbiota and by increased production of short-chain fatty acids (SCFA) [95]. Intestinal fermentation and health benefits of fructo-oligosaccharides, galacto-oligosaccharides and xylo-oligosaccharides have been well documented in animal and human studies [96, 97]. Recently, stimulation by isomalto-oligosaccharides (IMO) of the growth of intestinal lactic acid bacteria in a rat model was also shown by Ketabi et al. [95]. The relationship between diet, intestinal microbiota and host nutrition is currently under active investigation, and the integration of the functional analyses of gut microbiota and sourdough genomes and metagenomes may allow for design of prebiotic molecules with specific functional properties [98].

Microbes are able to produce a variety of polysaccharides. Exopolysaccharides (EPS) are sugar biopolymers that are secreted by bacteria, microalgae and by some yeasts and filamentous fungi. They may protect cells from external stress factors such as desiccation and antimicrobial substances, and mediate interactions of cells with surfaces and other cells, thus playing an important role, for instance, in biofilm formation. EPS can be divided into capsular polysaccharides that are more or less tightly bound on cells, and extracellular slime which cells excrete to their surrounding medium. EPS production can usually be detected on solid and liquid medium, respectively, from a slimy or ropy colony appearance and from an increase in medium viscosity. Microbial EPS vary greatly in mass; from ~10 kDa to 1–2 mDa. On the basis of their chemical composition, all microbial EPS can be broadly divided into homopolysaccharides (=Hops), consisting of only one monosaccharide type, and heteropolysaccharides (=Heps), made of two or more different monosaccharide units. Additionally, various inorganic or organic constituents may be attached. The possible complexities of polysaccharide structures are almost infinite as, for instance, even a disaccharide may be linked in eight different ways [99, 100].

Lactobacilli from wheat and rye sourdoughs have been shown to produce EPS [9, 101], and especially gluco-oligosaccharides [102] and fructo-oligosaccharides, which have prebiotic properties [9]. For example, *Lactobacillus sanfranciscensis* LTH2590 produced 0.5–1% levan (flour basis) during 24-h fermentation in wheat and rye doughs [101]. Tieking et al. [103] studied the ability of seven fructan- or glucan-positive LAB (*Lb. sanfranciscensis* LTH 2581 and 2590, *Lb. frumenti* TMW 1.103, 1.660, 1.669, *Lb. pontis* TMW 1.675, *Lb. reuteri* TMW

1.1.06) to produce these EPS during wheat dough fermentation in the presence of 12% sucrose (flour weight). For all the strains the production of the same EPS at a level of 0.5–2 g kg^{-1} was shown. Levans from *Lb. sanfranciscensis* may also exert probiotic effects as they are preferentially degraded by bifidobacteria in the intestinal tract [101]. Formation of oligo- and polysaccharides with prebiotic potential has also been shown by *Lb. reuteri* LTH5448 and *Weissella cibaria* 10 M in sorghum sourdoughs [104].

9.5 Future Prospects

Sourdough fermentation is a food processing method with a long history, traditionally used mainly to improve product quality. During the past 15 years, the use of microbial fermentation has also been proven to intensively modify the nutritional quality of cereal foods. Because of complex microbial and food structure interactions present in a sourdough system, fermentation can be tuned for multi-functional nutritional modifications of both traditional and novel fermentable substrates.

In the future, sourdough technology can provide an effective means to utilise and upgrade side streams from both food and non-food processing, provide novel protein functionalities and produce completely novel oligo- and polysaccharides for new nutritional improvements such as fat or sugar replacement. They also show potential in producing and influencing bioavailability of minor food constituents with high biological activity. Next-generation fermentations with yeast and lactic acid bacteria can thus be considered effective cell factories to modify cereal and also other fermentable materials for nutritionally tailored food or feed.

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