Potential of sourdough for healthier cereal products

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Sourdough fermentation has a well-established role in improving flavour and structure of bread. However, the significant potential of sourdough fermentation to improve the nutritional properties of rye, oat and wheat products has gained much less attention, although the interest is at present increasing. Sourdough fermentation can modify healthiness of cereals in a number of ways: it can improve texture and palatability of whole grain, fibre-rich or gluten-free products, stabilise or increase levels of various bioactive compounds, retard starch bioavailability (low glycaemic index products) and improve mineral bioavailability. Many new interesting applications for sourdough remain still to be explored, such as the use of prebiotic starter cultures or production of totally new types of bioactive compounds.

Introduction

Cereal foods in various forms are an essential component of the daily diet. Nutritionally, they are an important source of carbohydrates, protein, dietary fibre (DF) and many vitamins and non-nutrients (food components not essential for growth but with potential biological functions such as fructans). Recent epidemiological findings have indicated a protective role of especially whole grain foods against several Western diseases (Jacobs, Meyer, Kushi, & Folsom, 1998; Liu et al., 2000; Pereira et al., 2002). DF was long considered the major health protective component of grains. There is now increasing evidence also of other protective compounds, such as oligosaccharides and phytochemicals, which together with DF are concentrated in the outer layers of the grains. The levels and also bioavailability of carbohydrates and various bioactive compounds (compounds effecting human physiological reactions with health relevance) can remarkably be influenced by processing.

There is growing consumer interest in health aspects of food, including functional food products with specific physiological functions of health relevance. However, good sensory properties remain a prerequisite for any successful food, and consumers also expect food to fulfill other criteria such as safety and convenience.

Sourdough fermentation has a well-established role in improving flavour and structure of rye and wheat breads (Brummer & Lorenz, 2003). However, the significant potential of sourdough fermentation to improve the nutritional properties of rye, oat and wheat products has gained much less attention, although the interest is at present increasing.

In principle, the whole grain or fractions of cereal grain can be modified by sourdough fermentation to improve nutritional value or promote healthiness of cereal foods as indicated in Fig. 1. A typical example of modifying the whole kernel is wholemeal baking of rye or wheat. Wholemeal flour is rich in fibre, minerals, vitamins and many phytochemicals (s.c. bioactive compounds) such as phenolic compounds, sterols, tocopherols and tocotrienols, lignans, and phytic acid. However, very few wholemeal products are on the market, because of the lack of palatable taste and appealing mouth feel. With sourdough processes the mouthfeel and palatability of wholemeal bread can be improved without removing any nutritionally important components. Sourdough baking processes also improve texture and flavour of bran-rich breads (Salmenkallio-Marttila, Katina, & Autio, 2001).

Potential of sourdough in fibre enriched products

Maybe the most well known way by which sourdough can increase the health potential of wholemeal cereals is
traditional rye bread baking. Without sourdough wholemeal rye or wheat-rye flour mixes are very difficult to process, and sourdough also provides aromatic and pleasing flavour, and improves overall quality and shelf life of whole grain breads. Thus, a traditional rye sourdough process not only improves flavour and texture of the rye products but enables consumption of wholemeal rye, which is well known for its high nutritional quality and health-promoting properties, and could not be used in bread making without the sourdough process.

Another example of the potential of sourdough is the ability to modify the bran fraction of the grain (rich in fibre) in such a way that larger amounts of bran can be utilised in breads. The nutritional importance of DF has been demonstrated in many studies. A typical Western diet contains less than 20 g/day, whereas the recommended daily intake is 25–30 g (Cummings & Frolich, 1993). Thus, at the moment most people eat too little fibre and these low levels of DF in Western diet contribute to a long list of diseases, ranging in severity from dental caries through constipation to obesity, colorectal cancer, coronary heart disease and type 2 diabetes.

During the last few decades, the recognised health benefits of DF have created a growing interest in increasing the fibre content of various foods and the introduction of fibre ingredients. As a result the number of new high-fibre products has grown extensively during recent years. However, when fibre in some form is used in baked products, it is necessary to make adjustments in various process parameters in order to obtain high quality, high-fibre products which are acceptable for the majority of the consumers.

The most common source of DF in baking is cereal bran, especially wheat bran. The use of barley bran derived from huskless or de-husked barley or oat bran derived from husked oat kernels is also becoming more widespread due to their high soluble DF content, in particular their content of mixed-linked β-glucan. However, additions of cereal bran, especially in such amounts that health benefits can be expected, cause severe problems in bread quality. According to Seibel (1983) addition of fibre causes the following technological changes: (i) increases dough yield; (ii) results in a moister and shorter dough; (iii) decreases fermentation tolerance (that is dough is able to keep the optimum volume a shorter time during proofing); (iv) decreases bread volume; (v) creates a crumb which is tense and non-elastic; and (vi) creates flavour changes depending on type of fibre and bread type.

One option to improve quality of such high-fibre wheat breads is to pre-soak or ferment wheat bran before it is added to the dough. Pre-soaking of wheat bran for one hour has been reported to have beneficial effects on loaf volume (Lai, Davis, & Hoseney, 1989; Lai, Hoseney, & Davis, 1989). Hydration of bran (15 min in an excess water at 10 or 97 °C) before addition to the dough increased loaf volume and improved bread quality in wheat bread containing 12% bran (Nelles, Randall, & Taylor, 1998). Nelles et al. (1998) proposed several possible mechanisms for the observed improvement: improved hydration of all brown flour components, lipoxygenase activation, and a washing out of free reduced-glutathione. Longer soaking times (4–16 h) or intermediate temperatures (25–30 °C) have not improved loaf volume (Salmenkallio-Marttila et al., 2001). Also, as the bran layer of the grain is always enriched with various
microbes, such as *Bacillus subtilis*, soaking of the bran in conditions which favour the growth of microbes has to be done with care in order to avoid any microbiological risks. Also, other safety aspects of whole grain cereals or fibre products should always be secured, e.g. presence of biotic or xenobiotic substances should be excluded.

Pre-fermentation of bran with yeast or in particular, with yeast and lactic acid bacteria improves loaf volume (Fig. 2) and crumb softness during storage (Salmenkallio-Marttila et al., 2001). Thus, sourdough technology can be utilised effectively also in high-fibre baking. The effectiveness of fermentation is assumed to be due to the activity of endogenous enzymes of flour, especially the amylases and proteases (Boskov-Hansen et al., 2002). The acids produced during fermentation lower the pH of the dough, thereby affecting the enzyme activity and gluten characteristics. The pH optima of carbohydrate-degrading enzymes, such as amylase, pentosanase, or β-glucanase, vary widely (pH 3.6–5.6) depending on wheat variety and germination status (Fox & Mulvihill, 1982). Gluten-associated proteinases of flour are usually active at pH levels below 4. The rapid drop in pH level in sourdough can cause reduced amylolytic activity, whereas the more gradual fall in pH level in spontaneously fermented dough permits further starch degradation. Modifications in starch during fermentation alter the structure of the gelatinised starch granules (Eynard, Guerrieri, & Cerletti, 1995; Siljeström et al., 1988).

Recently, Lopez et al. (2001) introduced also other beneficial effects of bran fermentation; in their study pre-fermentation of bran with lactic acid bacteria improved phytate breakdown (up to 90%) and increased magnesium and phosphorus solubility (for a more detailed description, see below).

**Influence of sourdough on the levels and stability of bioactive compounds**

Intake of whole grain foods is increasingly reported to be associated with health benefits, including improved regulation of blood glucose levels and decreased risk of diabetes, cardiovascular disease, and certain cancers (Jacobs et al., 1998; Liu et al., 2000; Pereira et al., 2002). In addition to DF, grains contain a wide range of nutrients and bioactive compounds, which have been suggested to contribute to the positive health effects. These phytochemicals, such as lignans, phenolic acids, phytosterols, tocopherols and tocotrienols, and other vitamins, are concentrated in the germ and in the outer layers of the kernel (Glitsø & Bach Knudsen, 1999; Hegedüs, Pedersen, & Eggum, 1985).

Processing is a prerequisite for manufacturing attractive whole grain products and increased consumption of whole grains. Processing must first of all render the food a suitable form and good palatability. Processing also is important in increasing extractability of nutrients and non-nutrients (Clydesdale, 1994). Processing may decrease or increase the levels of the bioactive compounds in grains, and also modify bioavailability of these compounds, as reviewed recently by Slavin, Jacobs, and Marquardt (2000).

Sourdough processes can be used to modify levels of bioactive compounds. However, there is not much data available. Sourdough fermentation has been reported to

![Fig. 2. Effects of sourdough fermentation on bread volumes of bran-enriched breads (20% bran). *sample differs significantly from the control bread (P<0.05). Adapted from Salmenkallio et al. (2001).](image-url)
increase folate content (Kariluoto et al., 2004; Liukkonen et al., 2003), decrease tocopherol and tocotrienol content (Liukkonen et al., 2003; Wennemark & Jaegerstad, 1992), and decrease or increase thiamin content depending on the process (Ternes & Freund, 1988). Thus, sourdough fermentation can both increase or decrease the levels of bioactive compounds depending on the nature of the compound and the type of the sourdough process. The presence of yeast seems to favour formation of folates (Kariluoto et al., 2004) and thiamin (Ternes & Freund, 1988). Formation of acidity can both increase levels of bioactive compounds (such as total amount of phenolic compounds) or decrease levels of some compounds (such as thiamin, ferulic acid dehydrodimers, tocopherols and tocotrienols) (Boskov-Hansen et al., 2002; Liukkonen et al., 2003; Ternes & Freund, 1988). The degradation of phytate, already discussed above, has repeatedly been reported in sourdough processes (Angelis et al., 2003; Lopez et al., 2001; Turk, Carlsson, & Sandberg, 1996). The mechanisms of increase or decrease of the levels of bioactive compounds in sourdough fermentation are mainly unknown. Role of acidity was partly illustrated in the recent paper of Liukkonen et al. (2003), in which the influence of rye sourdough fermentation with two different rye varieties (Amilo and Akusti) was studied on several bioactive compounds, including phenolic acids, sterols, folates, tocopherols and tocotrienols, and lignans. Also, the influence of fermentation on total amount of phenolic compounds after methanol (more easily extractable compounds) and alkaline extraction was determined. The studied varieties had different falling numbers (FN) and grain size; large-grained Amilo had FN 200 and small-grained Akusti had FN value 110, respectively. Both varieties were fermented with a mixture of Saccharomyces cerevisiae, Lactobacillus brevis and L. plantarum (mimicking an industrial starter), and identical sourdough fermentation and subsequent baking processes were utilised. After fermentation, Akusti-sourdough was more acidic (pH and total titratable acidity (TTA) values were 3.9 and 17.0, respectively) in comparison to Amilo (pH and TTA values were 4.9 and 9.0, respectively), due to different FN of the varieties.

As seen in Fig. 3, the fermentation phase more than doubled the levels of folates and easily extractable phenolic compounds. The levels of tocopherols and tocotrienols reduced during the sourdough fermentation, probably due to contact with air (Piironen, Varo, & Koivistoinen, 1988), while the amounts of sterols, alk(en)ylresorcinols, lignans, phenolic acids and alkaline extractable phenolic compounds changed very little. The fermentation stage also increased the antioxidativity (DPPH radical scavenging activity) in the methanol extracted fraction, probably due to increased levels of easily extractable phenolic compounds.

Flander, Salmenkallio-Marttila, Suortti, and Autio (2003) optimised the oat baking process both in terms of the bread quality and the physiological functionality of oat β-glucan in bread. The breads were baked from whole grain oat flour (51% of total amount of flour) and white wheat flour (49%). Specific volume, instrumental firmness, sensory quality, sourness (pH, TTA, lactic acid content), and concentration and molecular mass of β-glucan of the breads were analysed. Tasty bread with good volume, structure and keeping qualities was attained by optimising sourdough fermentation and subsequent baking variables. In straight dough baking about 30% of the β-glucan was...
degraded. In sourdough baking β-glucan was preserved (0.8 g/serving) (Flander, Salmenkallio-Marttila, Suortti, & Autio, 2004). Acidity was a protective factor for β-glucan in bread. The molecular mass of β-glucan in breads was lower than that of the oat flour. This study improved the possibilities to use oat as a health-promoting ingredient in bread.

Influence of sourdough on starch digestibility

Sourdough has also great potential to modify the macromolecules in the dough, the most well known examples being the ability of sourdoughs to reduce digestibility of starch (Liljeberg, Lönner, & Björck, 1995; Östman, Nilsson, Liljeberg-Elmstähl, Molin, & Björck, 2002).

Food-related diseases, such as obesity and type 2 diabetes, are becoming a tremendous threat to the health and well being of many people in the Western world and also in China and India. The carbohydrates in a Western diet originate to a large extent from rapidly digestible sugars and starch. White wheat bread, most rice products, potato and many breakfast cereals are examples of common starchy foods producing high glycaemic responses (Foster-Powell, Holt, & Brand-Miller, 2002). The concept of glycaemic index (GI) was developed over 20 years ago (Jenkins, Wolever, Taylor, et al., 1981). The GI of food is a ranking of foods based on their immediate effect on blood glucose levels (Foster-Powell et al., 2002; Wolever, Jenkins, Jenkins, & Josse, 1991). These tables are useful for diabetic patients for guiding to choose proper foods. The extent to which food characteristics affect postprandial insulinemia has not been well studied. Holt, Brand-Miller, and Petocz (1997) have recently shown that protein- and fat-rich foods induced as much insulin secretion as did some carbo-hydrate-rich foods in healthy subjects.

Various ways of processing can also create a food that is slowly broken down during chewing and stomach phase, rendering the starch less rapidly available for digestion. For example, the compact structure of pasta is the main reason for the low GI of this food group (Granfeldt & Björck, 1991). Starch in breads baked from white wheat flours generally evokes rapid glucose responses (Holm & Björck, 1992). The lowest GI values (66–80) have been reported for pumpernickel-type breads containing intact kernels (Jenkins et al., 1981, 1986; Wolever, Jenkins, Josse, Wong, & Lee, 1987).

The intact botanical structure protects the encapsulated starch of the kernel against the hydrolysis by gastrointestinal amylolytic enzymes (Granfeldt, Björck, Drews, & Tovar, 1992). 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 (Juntunen et al., 2003). Both rye bread types were baked with a sourdough process and with 40% of a total amount of rye flour being pregerminated before incorporating 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 due to the presence of organic acid formed during sourdough fermentation (Autio et al., 2003).

Organic acids also have been shown to play a role in the postprandial glycaemic responses. They may be present in the raw foods, produced upon fermentation processing (such as sourdough fermentation) or added, as in the case of pickled food. Certain acids, such as acetic, propionic, and lactic acid have the ability to lower the postprandial blood glucose and insulin responses, when included in bread meals. In the case of acetic acid added to bread meals, both Brighenti et al. (1995) and Liljeberg and Björck (1998) have shown blood glucose lowering effects. In the study by Liljeberg and Björck (1998), a lowered gastric emptying rate was detected suggesting that the effect was due to the firm texture of the bread. A lowered gastric emptying rate was not reported by Brighenti et al. (1995). The presence of lactic acid in bread, either added or formed during sourdough fermentation, has also been reported to reduce acute glycaemic and/or insulinaemic responses (Liljeberg et al., 1995). However, the lowering of glycaemic and insulinaemic responses of breads with added lactic acid could not be attributed to a reduced gastric emptying rate (Liljeberg & Björck, 1996). The role of a reduced rate of starch digestion in lowering glycaemia in bread containing lactic acid was confirmed recently by Östman et al. (2002). Furthermore, their work suggested that the presence of lactic acid during heat treatment promotes interactions between starch and gluten, hence reducing starch bioavailability.

Sourdough and mineral bioavailability

Wholemeal cereals are an important source of minerals such as K, P, Mg, or Zn, but unfortunately mineral utilisation is limited by the presence of phytic acid (Lopez, Remesy, & Demigne, 1998). Wheat and rye contain about 2–58 mg/g phytic acid, which is localised in the aleurone layer of the kernel as the magnesium–potassium salt (Garcia-Estepa, Guerra-Hernandez, & Garcia-Villanova, 1999). Phytic acid is highly charged with six phosphate groups, and it forms insoluble complexes with dietary cations, thus hindering mineral bioavailability (Lopez et al., 1998).

Reduction of phytic acid content during bread making depends on phytase action. As with other enzymatic reactions, various factors contribute to phytate degradation in doughs, including phytase activity, particle size of the meals, pH, temperature, water content, and fermentation time (Angelis et al., 2003; Fretzdorff & Brummer, 1992; Harinder, Tiwana, & Kaur, 1998). Phytate-degrading enzymes exist in cereals, yeast and lactic acid bacteria isolated from sourdoughs (Lopez et al., 2000; Shirai,
Reval-Molsey, Garcia-Garibay, and Marshall, 1994; Turk et al., 2000). Reduction of phytic acid content in different bread types may vary between 13 and 100%, the highest levels of phytic acid obtained with unleavened breads (Lopez et al., 2001).

In general, low pH favours degradation of phytic acid, optimal pH value for hydrolysis being 4.5 in wheat and rye doughs according to Fretzdorff and Brummer (1992). Thus, use of sourdoughs or acidified sponges can be adjusted to improve mineral bioavailability by increasing phytic acid hydrolysis. In the recent work of Lopez et al. (2001), the influence of yeast fermentation, and sourdough fermentation without and with yeast, were compared on degradation of phytic acid. Their results show that both types of sourdough fermentation reduces phytic acid content up to 62%, whereas conventional yeast fermentation reduced it only by 38%. Furthermore, acidification formed during sourdough fermentation also increased magnesium and phosphorus solubility with 20–30%. This effect was even more pronounced if the bran fraction of wheat (rich in phytic acid) was fermented with lactic acid bacteria; the percentage of phytic acid breakdown was near 90%, whereas 40% of phytate was remained in traditional French bread (Lopez et al., 2001).

Sourdough and coeliac disease

Coeliac disease (CD) or in the USA celiac disease (also known as non-tropical sprue, gluten-sensitive enteropathy, celiac sprue, idiopathic steatorrhea, primary malabsorption, Gee–Herter disease, gluten-induced enteropathy, adult coeliac disease) is a condition, where the person’s body reacts to the gliadin fraction of wheat and the prolamins of rye (secalins), barley (hordeins) and possibly oats (avidins) (Murray, 1999). The reaction to gluten ingestion is inflammation of the small intestine leading to the malabsorption of several important nutrients, including iron, folic acid, calcium and fat-soluble vitamins (Feighery, 1999; Kelly, Feighery, Gallagher, & Weir, 1999). The Codex Alimentarius Commission (1994, 2000) of the World Health Organization (WHO) and the Food and Agricultural Organisation (FAO) stated in a draft revised standard for gluten-free foods, that so called ‘gluten-free’ foods are described as: (a) consisting of, or made only from, ingredients which do not contain any prolamins from wheat or all Triticum species such as spelt (Triticum spelta L.), kamut (Triticum polonicum L.) or durum wheat, rye, barley, oats or their crossbred varieties with a gluten level not exceeding 20 ppm or (b) consisting of ingredients from wheat, rye, barley, oats, spelt or their crossbred varieties which have been rendered ‘gluten-free’, with a gluten level not exceeding 200 ppm or (c) any mixture of two ingredients as in (a) and (b) mentioned with a level not exceeding 200 ppm.

The only way that CD can be treated is the total lifelong avoidance of gluten ingestion. A review presented by Kasadra (2001) suggests that species, which are less closely related to wheat such as sorghum, millet, treff, ragi and Job’s tears as well as pseudocereals such as buckwheat, amaranth and quinoa, are safe for the consumption of persons suffering of CD. The total avoidance of gluten and gluten-related proteins leads to a recovery of the mucosa. Patients with CD are unable to consume some of the most common products on the market today, namely breads, baked goods and other food products made with wheat flour (Lovis, 2003). Gluten removal results in major problems for bakers, and currently many gluten-free products on the market are of low quality, exhibiting poor mouthfeel and flavour (Arendt, O’Brien, Schober, Gormley, & Gallagher, 2002).

Recent epidemiological studies have shown that the prevalence of CD has been significantly underestimated (Ascher & Kristiansson, 1997; Fasano & Catassi, 2001; Horvath & Mehta, 2000; Johnson, Watson, McMillan, Sloan, & Love, 1997). In Europe the prevalence of CD has been estimated to be 1 in 300 to 1 in 500 persons but recent population-based screening studies suggest that the prevalence is as high as 1 in 100 (Mustalathti et al., 2002). Recent studies have shown that CD is as frequent in the United States as in Europe (Fasano & Catassi, 2001). The iceberg is a common model used to explain the epidemiology of CD (Visakorpi, 1996). According to Stern (1992) the tip of the iceberg is formed by patients who have just been diagnosed by biopsy, demonstrating a flat mucosa. The lower part of the tip is formed by patients who have been recently diagnosed and who are now living gluten-free and show a normal mucosa. Below the waterline there is a big group of ‘silent’ cases, which have not been identified and have a flat small intestine mucosa. They may remain undiagnosed because the condition has no symptoms (Feighery, 1999). Just at the bottom there is a small group of patients with latent coeliac disease showing a normal mucosa while taking gluten.

Gluten-free breads are the biggest challenge of all cereal products due to the fact that wheat gluten has such a wide variety of tasks in bread making, so a wide range of ingredients is needed to achieve a good quality product without it. The majority of the gluten-free flours as well as gluten-free products currently on the market are wheat starch based and can therefore threaten the health of a CD patient, due to the very small amount of gluten that might be still present.

There are no published reports on the impact of lactic acid bacteria on the quality of gluten-free breads. In the present paper some of the data generated during a recent study are presented (Arendt, unpublished data). Gluten-free breads tend to show quick staling and a flat aroma. It has been reported for wheat bread that both of these disadvantages can be overcome by the application of sourdough (Clarke, Schober, & Arendt, 2002; Crowley, Schober, Clarke, & Arendt, 2002). In this study, the influence of sourdoughs made from different strains of lactic acid bacteria on the quality of gluten-free bread containing...
over a 5-day storage period was evaluated. The sourdough-containing breads were compared to a non-acidified control and a chemically acidified control. The chemically acidified control was acidified with lactic acid at the same level as produced by the bacterial cultures. The gluten-free recipe used in these studies was based on brown rice, soya, buckwheat flour and xanthan gum. The growth behaviour of the selected lactic acid bacteria was similar to that reported for wheat bread (Clarke et al., 2002).

Bread volume and height showed no significant difference between the breads nor did the number of cells and mean cell area derived from digital image analysis. Over storage time, breads tended to shrink, as indicated by a significant decrease in height. At the same time crumb hardness increased significantly for all breads. No significant differences in hardness were found between fresh breads after 2 days of storage. After 5 days of storage, however, the biologically acidified breads yielded significantly softer bread than the chemically acidified control as well as the non-acidified control. In triangle tests gluten-free sourdough bread could be discriminated from the control breads and was clearly preferred.

Empirical rheological tests (forward extrusion) were used to analyse the changes in batter viscosity of the sourdough itself over time as well as the viscosity of the sourdough-containing bread batters. The results revealed that the addition of sourdough led to an increase in batter viscosity, when bread batter was examined, whereas during the sourdough fermentation the viscosity decreased. The same has been reported for the rheological changes in wheat dough (Wehrle & Arendt, 1998). Changes in dough structure could not only be detected by small deformation viscoelastic measurements but also by confocal laser-scanning microscopy (Fig. 4). The protein fraction of the gluten-free sourdough was degraded over time (Fig. 4), this process was, however, far less obvious in a gluten-free system than with gluten isolated from wheat based sourdough (Fig. 4; Clarke, Schober, Dokery, O’Sullivan, & Arendt, 2004). When the sourdoughs were incorporated at a 20% level into the gluten-free batter no significant differences were observed in the structure (Fig. 5), which is not the case in wheat dough containing 20% sourdough (Fig. 5; Clarke et al., 2004). Overall it can be concluded that it is possible to produce sourdough from gluten-free base and the addition of such sourdough to gluten-free batters does lead to an improvement of the gluten-free-bread.

Conclusions and future trends

Sourdough has proven useful in improving the texture and palatability of whole grain and fibre-rich products, and it may stabilise or increase the levels of bioactive compounds. More applications are expected to fully utilise the potential of sourdoughs in this respect. The production of prebiotic oligosaccharides by sourdough lactic acid bacteria also is an interesting possibility. Sourdough has

![Fig. 4](image_url). Confocal laser-scanning micrographs of gluten-free sourdough and wheat sourdough at 0 h and after 24 h (magnification bar corresponds to 50 μm). Adapted from Clarke et al. (2004).

![Fig. 5](image_url). Confocal laser-scanning micrographs of gluten-free batter with 20% sourdough and wheat dough with 20% sourdough. Adapted from Clarke et al. (2004).
also shown useful in production of breads with slow starch digestibility and hence low glycaemic responses. Specific modifications in baked product texture can be achieved by development of new sourdough cultures, and by optimising acidity and interactions with grain components. Texture improvement is especially important in production of gluten-free bread, where the demand for good texture is especially challenging. Using mathematical modelling in sourdough process design may facilitate to define process conditions which enable a combination of health benefits with good sensory quality. The use of sourdough should also be extended to other products than bread: the production of healthy snacks, biscuits, and other types of convenience foods by using sourdough or fermented cereal ingredients remains to be explored.

References


