Determination of FODMAP contents of common wheat and rye breads and the effects of processing on the final contents

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Abstract

The benefits of a diet, low in fermentable oligo-, di- and monosaccharides and polyols (FODMAP) for patients suffering from irritable bowel syndrome (IBS) has been well established. Thus, the exact knowledge of the amount and composition of FODMAPs in foods is of vital importance for these patients. This study investigated the possibilities of FODMAP reduction by adjusting the processing parameters, which are feasible in practise, while still producing marketable breads. Therefore, the impact of prolonged proofing and the addition of sourdough on the FODMAPs in the final products was evaluated. High performance anion exchange chromatography was used for qualitative and quantitative analysis. A prolonged proofing time resulted in reduction of the fructan content and in consequence of the total FODMAPs. In contrast, the addition of sourdough only altered the FODMAP composition, by reducing the fructan content but increasing the mannitol content. While all the breads produced from refined wheat flour meet the low-FODMAP criteria, the breads from rye and whole meal wheat flour have to be considered as high-FODMAP, regardless of the processing conditions investigated. Breads produced from rye flour exceeded the limits for fructans and mannitol, while whole meal wheat breads were found to exceed the threshold for excess fructose. Overall, the production of low-FODMAP rye breads was identified as the biggest challenge for future research, since it could not be achieved using conventional processing parameter.

Keywords FODMAP · Bread · Fermentation time · Sourdough · Wheat · Rye

Introduction

One of the most common gastro-intestinal (GI) functional disorders is known as irritable bowel syndrome (IBS). The symptoms and impact on the patient's well-being and life quality are highly variable between individuals. The diagnosis of IBS is further complicated by the broad variety of possible causes for the disease. For approximately half of the patients, a food sensitivity appears the most plausible cause. Food components inducing problems were identified as non-digestible, osmotically active and by GI microorganisms fermentable carbohydrates, which are combined under

the acronym of FODMAP (fermentable oligo-, di- and monosaccharides, and polyols). Alongside short chain saccharides, such as fructose and lactose, this includes fructo- and galacto-oligosaccharides (FOS and GOS), which belong to the group of dietary fibres. While for healthy consumers these fibres can impact the (gastro-intestinal) health positively, they were shown to cause discomfort to IBS patients [1].

The carbohydrates classified as FODMAP are not hydrolysed and absorbed in the small intestine but then rapidly fermented by the bacteria inside the terminal ileum and large intestine. The symptoms induced include diarrhoea, abdominal pain, flatulence and bloating [1]. In general, these symptoms are reported after a FODMAP intake exceeding 0.3 g/kg body weight [2]. Varney et al. [3] published a more detailed study on the definition of cut-off values for low-FODMAP foods. For cereal products this includes limits of 0.15 g fructose in excess of glucose, 0.3 g total oligosaccharides, 0.4 g total polyols (or 0.2 g mannitol or sorbitol) and 1 g lactose per serving. Foods exceeding any of these values are regarded as high-FODMAP, as they were found

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to induce symptoms. Due to the highly individual nature of the human GI microbiota, occurrence and severity of the symptoms can vary greatly between individuals. It is striking, however, that 60% of patients diagnosed with fructose intolerance also show symptoms of IBS [4].

Among the major staple foods in European diets are various bakery products, primarily bread [5]. Unfortunately, cereals, such as rye and wheat, used for the production of bread are a major source of FODMAPs in human nutrition [6, 7]. The predominant saccharide in wheat and rye is starch, followed by oligosaccharides, such as fructans and raffinose, but also sucrose [8]. In addition, cereals also contain other polysaccharides, such as arabinoxylans and β -glucans which also belong to the group of dietary fibres [9]. Monosaccharides are present only in low concentrations [10].

The primary components in these cereal grains leading to IBS symptoms are fructans [11]. These contain on average 5–6 fructose units, are often branched chained (graminan-type) [12] and are mainly located in the bran layer of the kernels [13].

The exact fructan content of cereals depends on numerous factors, such as the type and variety, growing location, environmental conditions during growth and the level of maturity [14]. As a result, varying fructan contents of the whole kernel, ranging between 0.7 and 2.9% dry matter (DM) [14–17], were reported for soft winter wheat, a common variety for bread making. For flours with low mineral content, fructan concentrations of 1.4–1.7% DM were determined [15, 17]. From the substantially different fructan concentrations between whole kernel and flour, as well as the high fructan content of the bran (3.4–4.0% DM [15, 17]), an inhomogeneous distribution of the fructans within the kernel can be concluded.

Rye was reported to contain with 3.6–6.6% DM [14, 18] higher fructan concentrations compared to soft winter wheat. However, it also shows the highest concentrations in the bran (4–7% DM), while for flours with low mineral content only fructan contents of 2–3% DM are reported [15, 17].

The use of microbial fermentation processes during bread-making presents a possibility for the reduction in FODMAP content due to microbial metabolism. A comprehensive review explaining the complex metabolic pathways of microorganisms that use cereal carbohydrates in a dough system was recently published by Lopenen and Gänzle [19].

During bread production, fructans are partially degraded by the invertase released by *Saccharomyces cerevisiae*, the most commonly used baker's yeast. This allows a reduction of the total fructan content in wheat bread to 1–1.5% and in rye to approximately 3% [20–22]. However, with increasing degree of polymerisation of the fructans, the efficiency of the invertase decreases [21, 23]. A prolonged proofing time is a potential approach to

increase fructan degradation and reduction in excess fructose. Both factors contribute to lower FODMAP content in the final bread. First studies investigating the effects of excessive proofing times have shown promising results [10].

In addition, breads can be prepared using sourdough. Utilising sourdough for the production of breads generally results in much longer fermentation times compared to the use of yeast only. Traditionally, sourdough preparations are fermented for up to 33 h at a temperature ranging between 16 and 30 °C, applying up to 3 fermentation steps (“Auffrischen”). Of particular interest are here the Detmold 3- and 1-step procedures [24, 25]. In addition, a longer sourdough fermentation time improves the yeast population in the dough. Microorganisms most commonly found in sourdough are lactic acid bacteria (LAB) belonging to the species of *Fructilactobacillus sanfranciscensis*, *Levilactobacillus brevis*, *Lactiplantibacillus plantarum* and *Limosilactobacillus reuteri*, as well as yeast, such as *S. cerevisiae* [26, 27]. During the previous two decades, sourdough became popular in bread production for its improvement of aroma, texture and shelf life. Simultaneously, this process changes the quality and composition of the nutrients present in the flour.

To date, studies to exploit the metabolic pathways to reduce FODMAP contents in baking products were carried out in model systems on laboratory scale [21, 28]. To the best of the authors knowledge, no reports regarding the reduction of FODMAPs in breads produced on pilot scale are available. Since the applicability and, therefore, practical relevance of lab-scale productions is very limited, the present study is aimed to fill in this knowledge gap. Therefore, it was aimed at the analysis and reduction of FODMAP content and composition of various breads produced by commercially established practices. The modifications in the production process were only applied to the point where the resulting bread would meet consumer acceptance and marketability. For bread production, commonly used refined and whole meal flours of wheat and rye were applied. The particular interest of this work originates from the lack of research giving detailed information on the production of low-FODMAP rye breads. While a recent report investigated the reduction of fructans in rye breads, the resulting breads were not sufficient to achieve the low-FODMAP claim, demonstrating the need for further research [29]. During preparation, proofing times, as well as the addition of sourdough were investigated for their impact on the FODMAPs. In addition, potential of a FODMAP reduction, while maintaining good bread quality, by optimising these processing parameters was investigated. As a consequence, this study provides valuable knowledge towards the production of a wide product variety of low-FODMAP bread with high consumer acceptance.

Materials and methods

Materials

For the production of the baked goods, equipment was used as it is found in practice.

The following equipment was used during bread production, proofing cabinet model G 86W (Manz Backtechnik GmbH, DE), long formingmaschine Frilado type II (Frilado Bäckerei-Maschinenfabrik, DE), baking oven Daub Backmeister (Daub Backtechnik GmbH, DE).

Baker's yeast was derived from Uniferm GmbH & Co. KG (DE), and sourdough starter "Reinzucht-Sauerteig" from Böcker (DE). Chemicals were acquired from Roth (DE) in analytical quality.

Wheat flour type 550 (German classification, mineral content 0.51–0.63% DM) and rye flour type 1150 (German classification, mineral content 1.11–1.30% DM) were purchased from Roland Mills North (DE). Whole meal wheat flour and whole meal rye flour were from own production (MRI, mill pilot plant).

Production of breads

All breads were made according to typical recipes from the European region.

Levain

In practice, sourdough starters are initially used for the production of sourdough. These starters contain defined microorganisms which guarantee reliability compared to the spontaneous fermentation in the production process. According to the product specification sheet, the "Reinzucht-Sauerteig" starter contained *F. sanfranciscensis* (1×10^9 cfu/g $\pm 50\%$) and *Candida milleri* (5×10^6 cfu/g $\pm 50\%$). All sourdoughs described in the following were produced with flour, water and levain. For the levain 200 g of the corresponding flour were mixed with 200 mL water and 20 g sourdough starter and fermented at 26 °C for 16 h. The levain was stored at 5 °C for a maximum of one week.

Standard wheat bread with and without sourdough

The recipe ingredients for the standard wheat breads are summarised in Table 1.

After preparation of the sourdough, all components were processed into doughs with a "Stefan-Mixer" (UM 12-D, universal rapid kneader, Stephan u. Söhne GmbH & Co., DE), level 2, with a kneading time of 1 min. The doughs rested for 20 min in a proofer cabinet at 32 °C and 80%

Table 1 Recipe ingredients of wheat breads

	Standard	With sourdough
Sourdough		
Wheat flour type 550		150 g
Water		150 mL
Levain		15 g
Fermentation		26 °C, 16 h
Main dough		
Wheat flour type 550	1000 g	850 g
Water	580 mL	430 mL
Yeast	50 g	50 g
Salt	15 g	15 g
Sucrose	10 g	10 g
Peanut fat	10 g	10 g

humidity. The doughs were each divided into two equal pieces and rounded by hand. The doughs were covered and allowed to rest for 10 min at room temperature. The pieces of dough were long-formed using a long-forming machine and transferred into box pans. The unit fermentation took place at 32 °C and 80% humidity for 60 min (normal fermentation) and 80 min (long-term fermentation), respectively. The doughs were then baked at 220 °C for 40 min.

Breads Ciabatta style

For the ciabatta breads, a pre-dough must first be made from 300 g wheat flour type 550, 1.5 g baker's yeast and 150 mL water. This pre-dough was fermented for 5 h at 26 °C and for 15 h at 6 °C. The dough was made from the following recipe ingredients: 600 g wheat flour type 550, 450 g pre-dough, 100 g rye flour type 1150, 560 mL water, 20 g baker's yeast, 20 g olive oil, 20 g salt, 20 mg ascorbic acid. All recipe components were processed into a dough with a spiral kneader (SP 12 D, Diosna, Germany) with a kneading time of 8 min. After resting for 90 min at room temperature, the dough was divided into pieces of 600 g. The unit fermentation took place at 22 °C and 50–60% humidity for 90 min (normal fermentation) and 120 min (long-term fermentation), respectively. The doughs were then baked at 240 °C for 30 min.

Whole meal wheat bread with and without sourdough

The recipe ingredients for the wholemeal wheat breads are summarised in Table 2.

All recipe components were processed into a dough with a spiral kneader with a kneading time of 5 min. The dough rested for 30 min in a proofer cabinet at 32 °C and 80% humidity. Subsequently, the dough was formed by hand and transferred into box pans. The unit fermentation

Table 2 Recipe ingredients of whole meal wheat breads

	Standard	With sourdough
Sourdough		
Whole meal wheat flour		60 g
Water		60 mL
Levain		6 g
Fermentation		26 °C, 16 h
Main dough		
Whole meal wheat flour	600 g	540 g
Water	420 mL	360 mL
Yeast	12 g	12 g
Salt	9 g	9 g
Sucrose	6 g	6 g
Peanut fat	6 g	6 g

took place at 32 °C and 80% humidity for 60 min, followed by baking at 210 °C for 50 min.

Rye breads

Rye breads with three different sourdough processes were produced with rye flour type 1150 and whole meal rye flour, respectively. The sourdough processes were:

“Berlin short-term fermentation” (BST), sourdough process with commercial sourdough starter.

“Detmold one-step fermentation” (D1S), middle-term fermentation sourdough process.

“Detmold three-step fermentation” (D3S), long-term fermentation sourdough process.

The fermentation conditions and the recipe ingredients are summarised in Table 3.

The preparation of the sourdoughs for the “Detmold three-step fermentation” is summarised in Table 4.

The doughs were mixed in a pedalkneader (laboratory scale, Diosna, Germany) for 1 min at level 1 and for 2 min at level 2. The dough rested for 15 min at room conditions. The dough was then formed by hand and transferred to a fermentation basket. The unit fermentation took place at 32 °C and 80% humidity for 40 min. The dough was then baked at 260 °C for 7 min and at 220 °C for 53 min.

Sample preparation

Samples of the bread crumb were cut into cubical pieces and pre-dried at 40 °C until constant weight. The pre-dried bread samples were then ground to a particle size < 0.5 mm, using a disk-mill (Retsch, Germany). To calculate the results based on dry matter, the moisture contents of the flours and pre-dried breads was determined by drying for 90 min at 130 °C [30].

FODMAP extraction

The extraction of the FODMAP components from the flours and breads was based on the method previously published by Ziegler et al. [10] with some modifications. In brief, 1.0 ± 0.1 g of sample was weight into a 50 mL conical test tube and 2.0 mL of methanol were added and homogenised. Subsequently, 20 mL of distilled water (80 °C) were added and the mixture was homogenised. This suspension was then subjected to ultrasonication (VWR ultrasonic cleaner 120 W) for 2 min at 25 °C. After centrifugation (15 min, 1700 g, 20 °C), the supernatant was collected and the hot

Table 3 Recipe ingredients of rye breads and whole meal rye breads

	Breads from flour T1150			Whole meal breads		
	BST	D1S	D3S	BST	D1S	D3S
Sourdough						
Flour	450 g	300 g	450 g	240 g	180 g	240 g
Water	450 mL	300 mL	460 mL	240 mL	180 mL	270 mL
Levain	90 g	30 g	2.4 g (1st stage)	48 g	18 g	3.0 g (1st stage)
Fermentation	3.5 h, 35 °C	16 h, 26 °C	26 h, 16–30 °C	3.5 h, 35 °C	16 h, 26 °C	26 h, 16–30 °C
Acidity	12.7°, pH 4.0	18.3° pH 3.7	14.5°, pH 4.0	13.2°, pH4.0	18.7°, pH 3.7	14.5°, pH 4.0
Main dough						
Flour	550 g	700 g	550 g	360 g	420 g	360 g
Water	275 mL	415 mL	275 mL	210 mL	270 mL	180 mL
Sourdough	900 g	600 g	910 g	480 g	360 g	510 g
Baker;s yeast	10 g	10 g	10 g	6 g	6 g	6 g
Salt	15 g	15 g	15 g	9 g	9 g	9 g
Acidity of the final bread	11.0, ph 4.4	10.9°, p 4.3	11.3°, ph 4.3	1.8°, ph 4.3	12.2°, pH 4.3	12.3°, pH 4.2

Table 4 Preparation of the sourdoughs for the “Detmolder three-step fermentation”

	Rye flour type 1150	Whole meal rye flour
1st stage		
Flour	45 g	60 g
Water	45 mL	60 mL
Levain	2.5 g	3.0 g
Fermentation	26 °C, 7 h	
2nd stage		
Flour	150 g	84 g
Water	90 mL	48 mL
1st stage	20 g	12 g
Fermentation	26 °C, 16 h	
3rd stage		
Flour	300 g	180 g
Water	360 mL	260 mL
2nd stage	260 g	134 g
Fermentation	30 °C, 3 h	

water and ultrasound extractions were repeated twice. The volume of the combined supernatants was adjusted to 100 mL, using distilled water and filtered (pore size 0.45 µm) into an HPLC sample vial. All sample extractions were done in duplicate.

Determination of FODMAP using HPAEC-PAD

The sample extracts were analysed using high-performance anion exchange chromatography HPAEC Dionex ICS 5000+ (Sunnyvale, CA). The system was equipped with an AS-AP autosampler, an SP single pump (analytical gradient pump) and a 25 µL sample loop, using the “full loop injection” Detection was carried out with an ED electrochemical detector cell with a conventional gold working electrode and an Ag/AgCl reference electrode. The gold carbo quad waveform was used.

The chromatographic run was carried out according to the method previously published by Ziegler et al. [10] with some modifications. Separation was carried out, using a CarboPac PA 1 (4 × 250 mm) equipped with a CarboPac PA1 guard column, both operated at 25 °C. The mobile phase consisted of (A) 100 mM sodium hydroxide solution and (B) 100 mM sodium hydroxide in 600 mM sodium acetate. Eluents were degassed using helium and stored under helium atmosphere. Separation of carbohydrates was carried out using the following gradient program: 0–40 min 100% A, 40–55 min linear increase of B from 0 to 100%, 55–70 min 100% A. The total run time was 70 min at a flow rate of 1 mL/min with an injection volume of 25 µL.

Table 5 List of calibration standards with purity, supplier and calibration range

Standard	Purity (%)	Supplier	Calibration range (mg/L)
Fructose (D–)	99.0	Sigma Aldrich	1 30
Glucose (D+)	99.5	Sigma Aldrich	1 50
1,1,1-Kestopentaose	80.0	Megazyme	1 20
1-Kestose	98.0	Merck	1 20
Maltose-monohydrate (D+)	99.0	Sigma Aldrich	1 60
Mannitol (D–)	98.0	Sigma Aldrich	1 40
Nystose	98.0	Sigma Aldrich	1 10
Raffinose (D+) pentahydrate	99.0	Fluka Chemie AG	1 40
Sucrose	99.0	Sigma Aldrich	1 50
Sorbitol (D–)	98.0	Fluka Chemie AG	1 40

Calibrations were performed using different dilutions of analytical standards of mannitol, sorbitol, glucose, fructose, lactose, sucrose, maltose, raffinose, stachyose, kestose, nystose and kestopentaose in distilled water (Table 5). All calibrations were found to be linear in the respective calibration range ($R^2 > 0.99$). Identity of the peaks in the bread and flour samples was determined by standard addition. The limit of detection (LOD) and limit of quantification (LOQ) were determined by spiking of a standard wheat bread sample with the appropriate standard solution prior to extraction. LOD and LOQ were set for a signal to noise ratio of 3 and 10, respectively. Analyte concentrations below the LOQ were denoted as traces and concentrations below the LOD as n.d. (not detectable). All concentrations were calculated based on the sample dry matter.

Enzymatic quantification of fructans

The total Fructan content was determined, using the “Fructan Assay Kit (K-FRUC 10/18) from Megazyme (Bray, Ireland) according to the instructions given in the manual. To avoid the interference of galactooligosaccharides, the samples were incubated with α -galactosidase, as described in the manual. The analysis was carried out in duplicate on the pre-dried and ground samples. A reagent negative control and levan flour as positive control were analysed with each sample batch to ensure the validity of the results.

Statistical analysis

Statistical analysis was carried out using Microsoft Excel (Version 2019).

All bread recipes were prepared in independent duplicates. Two extractions of each bread and flour were carried out, analysed and the average used for statistical evaluation. The results were expressed as average $\pm$ standard deviation of the two baking repeats per bread recipe. Pairwise comparison of the results was carried out using Student's *t* test to determine whether differences were significant or not.

Results

Determination of FODMAP in flour varieties

Wheat flours

The commonly known FODMAPs identified in both wheat flours were raffinose, nystose, kestopentose and larger oligosaccharides, belonging to fructans. Furthermore, sucrose, maltose, fructose and glucose were detected in both wheat flours. The polyols mannitol and sorbitol, as well as kestose, stachyose and lactose were not detected in either of the wheat flours. However, the concentration of each component, except of kestopentose, varies significantly between the refined and whole meal wheat flour.

The quantification of the components detected, as well as the total fructan content and the total FODMAP content are summarised in Table 6.

The primary FODMAPs were fructans with concentration of 1185 ± 44 mg/100 g DM and 1687 ± 76 mg/100 g DM in the refined and whole meal wheat flour, respectively. In whole meal flour, raffinose was with 189 ± 1 mg/100 g DM the second most prominent FODMAP component. In contrast, a raffinose content of only 63 ± 1 mg/100 g DM was found in the refined wheat flour. Furthermore, concentrations of 105 ± 9 mg/100 g DM and 97 ± 2 mg/100 g DM for kestopentose, as well as 5 ± 1 mg/100 g DM and 16 ± 1 mg/100 g DM for nystose were determined in the refined and whole meal wheat flour, respectively. Although fructose was also found in both flours, it was not counted towards the total FODMAP content, as it occurs in both flours in a lower concentration compared to glucose. According to Gibson et al. [31] fructose only counts towards the FODMAP content if it occurs in excess of glucose. Consequently, the total FODMAP content of the refined wheat flour was summarised to 1248 mg/100 g DM, which is substantially lower compared to the whole meal flour with 1876 mg/100 g DM.

Rye flours

In similarity to the wheat flours, the oligosaccharides raffinose, nystose and kestopentose were detected in both rye flours. Furthermore, fructose and sorbitol were identified,

Table 6 Composition of relevant saccharides and polyols and total FODMAP content in wheat flour type 550 and whole meal wheat flour, results are given as (mg/100 g DM)

	Fructan total ^a	Kestopentose ^b	Kestose ^b	Nystose ^b	Fructose ^b	Raffinose ^b	Sorbitol ^b	Mannitol ^b	FODMAP Total ^c	Glucose ^b	Sucrose ^b	Maltose ^b
Wheat flour type 550	1185 ± 44	105 ± 9	nd	5 ± 1	106 ± 2	63 ± 1	nd	nd	1248	208 ± 1	562 ± 14	936 ± 6
Whole meal wheat flour	1687 ± 76	97 ± 2	nd	16 ± 1	204 ± 4	189 ± 1	nd	nd	1876	681 ± 2	157 ± 2	660 ± 27

^aData were obtained by AOAC 999.03

^bData were obtained by HPAEC-PAD

^cFODMAP total = sum of fructans (including fructooligosaccharides), galactooligosaccharides (stachyose, raffinose), lactose, excess fructose and sugar polyols, nd: not detectable

Table 7 Composition of relevant saccharides and polyols and total FODMAP content in rye flour type 1150 and whole meal rye flour

	Fructan total ^a	Kestopentaose ^b	Kestose ^b	Nystose ^b	Fructose ^b	Raffinose ^b	Sorbitol ^b	Mannitol ^b	FODMAP total ^c	Glucose ^b	Sucrose ^b	Maltose ^b
Rye flour type 1150	3239 ± 89	575 ± 2	nd	323 ± 1	1201 ± 14	61 ± 1	107 ± 1	nd	3407	2444 ± 1	125 ± 4	338 ± 2
Whole meal rye flour	3352 ± 50	546 ± 3	nd	305 ± 2	1500 ± 14	49 ± 1	69 ± 1	nd	3471	2960 ± 56	79 ± 6	343 ± 18

Results are given as (mg/100 g DS)

^aData were obtained by AOAC 999.03^bData were obtained by HPAEC-PAD^cFODMAP total = sum of fructans (including fructooligosaccharides), galactooligosaccharides (stachyose, raffinose), lactose, excess fructose and sugar polyols, nd: not detectable)

alongside larger oligosaccharides belonging to the fructans. In addition, the saccharides maltose, sucrose and glucose were found in both flours. No detectable amounts of stachyose, lactose, kestose and mannitol were evident in either of the two rye flours.

The results of the quantification of the saccharides and polyols found in the rye flours are summarised in Table 7.

For both flours, the most prominent constituents are fructans with a total concentration of 3239 ± 89 mg/100 g DM and 3352 ± 50 mg/100 g DM for refined and whole meal rye flour, respectively. The second most prominent FODMAP component was fructose, but as it was present in lower concentrations than the glucose it is not considered further for the evaluation of the FODMAP content [31]. The three oligosaccharides kestopentaose, nystose and raffinose were present in the refined flour at concentrations of 575 ± 2 mg/100 g DM, 323 ± 2 mg/100 g DM and 61 ± 1 mg/100 g DM. The whole meal flour contained slightly less of each of the three saccharides with concentrations determined to 546 ± 3 mg/100 g DM, 305 ± 2 mg/100 g DM and 49 ± 1 mg/100 g DM for kestopentaose, nystose and raffinose. Sorbitol was found at a significantly higher concentration in the refined flour (107 ± 1 mg/100 g DM) compared to the whole meal flour (69 ± 1 mg/100 g DM). No significant difference was evident between the calculated total FODMAP contents of the rye flours. These were found to be 3407 mg/100 g DM and 3471 mg/100 g DM for the refined and whole meal flour, respectively.

Effect of proofing time on FODMAPs

Standard wheat bread without sourdough

Neither of these breads contained detectable amounts of kestopentaose, kestose, nystose, stachyose, raffinose, sucrose, lactose or mannitol, regardless of their proofing time. The predominant component in both samples was identified as maltose. In addition, fructose, glucose and sorbitol could be identified in both breads but with visibly different concentrations. Finally, larger fructans were detected with numerous peaks and quantified using enzymatic determination.

The quantification of each component, the enzymatically determined total fructan and the calculated total FODMAP content are summarised in Table 8.

The predominant FODMAP components in both breads were found to be fructans. The total fructan content was determined to 338 ± 22 mg/100 g DM and 266 ± 59 mg/100 g DM for the standard and extended proofing time, respectively. Likewise, the concentration of fructose was found to be significantly reduced due to the extended fermentation time. The fructose contents of the respective 60 min and 80 min proofed breads were determined to 221 ± 1 mg/100 g DM and 99 ± 1 mg/100 g

Table 8 Composition of relevant saccharides and polyols and total FODMAP content in wheat breads type 550

	Fructan total ^a	Kesto- penta- ose ^b	Kestose ^b	Nystose ^b	Fructose ^b	Raffinose ^b	Sorbitol ^b	Mannitol ^b	FOD- MAP Total ^c	Glucose ^b	Sucrose ^b	Maltose ^b
Standard wheat bread, normal fermentation	338 ± 22	nd	nd	nd	221 ± 1	nd	60 ± 1	nd	528	91 ± 1	nd	4244 ± 197
Standard wheat bread, excessive fermentation	266 ± 59	nd	nd	nd	99 ± 1	nd	68 ± 1	nd	358	75 ± 1	nd	4135 ± 25
Wheat bread, sourdough, normal fermentation	242 ± 45	nd	nd	nd	118 ± 1	nd	57 ± 1	183 ± 1	523	78 ± 4	nd	4139 ± 23
Wheat bread, sourdough, excessive fermentation	218 ± 26	nd	nd	nd	53 ± 1	nd	71 ± 1	186 ± 2	474	64 ± 1	nd	2122 ± 51
Ciabatta, normal fermentation	480 ± 11	nd	nd	nd	329 ± 12	nd	45 ± 1	nd	685	169 ± 2	nd	4574 ± 367
Ciabatta, excessive fermentation	436 ± 61	nd	nd	nd	261 ± 1	nd	54 ± 1	nd	595	156 ± 1	nd	4443 ± 42

Results are given as (mg/100 g DM)

^aData were obtained by AOAC 999.03^bData were obtained by HPAEC-PAD^cFODMAP total = sum of fructans (including fructooligosaccharides), galactooligosaccharides (stachyose, raffinose), lactose, excess fructose and sugar polyols, nd: not detectable)

DM. Excess fructose for 60 min and 80 min proofed wheat bread was calculated to 130 mg/100 g DM and 24 mg/100 g DM, respectively. In comparison, a much smaller influence of the proofing time was found regarding the concentration of sorbitol, which was determined to 60 ± 1 mg/100 g DM and 68 ± 1 mg/100 g DM after standard and excessive proofing, respectively. Also, glucose and maltose were found in slightly lower concentrations as a result of the extended proofing time. Finally, the total FODMAP content for the white wheat bread with standard (60 min) and extended (80 min) proofing time was calculated to 528 mg/100 g DM and 358 mg/100 g DM, respectively.

White bread with sourdough

The influence of an extended (80 min) compared to standard (60 min) proofing time on white wheat breads produced with a sourdough was investigated, using the refined wheat flour. The results of the FODMAP determination are summarised in Table 8. The FODMAP components present in both breads are fructans, fructose, sorbitol and mannitol. In addition, glucose and maltose were also found in both wheat breads, regardless of the proofing time. No detectable amounts of kestopentaose, kestose, nystose, stachyose, raffinose, lactose and sucrose could be found in either of the pre-fermented breads.

The content of total fructans in the breads was determined to be substantially affected by the length of proofing of the dough. Hence, the standard and extended proofing resulted in total fructan contents of 242 ± 45 mg/100 g DM and 218 ± 26 mg/100 g DM in the final breads. Likewise, the concentration of fructose was also significantly reduced due to the longer proofing time. The fructose contents were determined to 118 ± 1 mg/100 g DM and 53 ± 1 mg/100 g DM for the 60 min and 80 min proofed breads, respectively. In contrast, the glucose concentration was found to be much less affected by the prolonged proofing, leading to the removal of excess fructose in these breads. In consequence, the excess fructose for the standard proofed breads was calculated to 40 mg/100 g DM, while no excess fructose was present in the extensively proofed breads. In contrast, the concentration of both polyols remained unaffected by the proofing time. The mannitol content did not change significantly with the proofing time and was found to be 183 ± 1 mg/100 g DM and 186 ± 2 mg/100 g DM for the standard and excessive proofing, respectively. For sorbitol, even an increased concentration was evident as a result of the prolonged proofing time. So, the sorbitol content increased from 57 ± 1 mg/100 g DM after 60 min proofing to 71 ± 1 mg/100 g DM after 80 min proofing. Overall, extending the proofing time of white

wheat breads with sourdough from 60 to 80 min led to a reduced FODMAP content. The longer proofing time resulted with 474 mg/100 g DM in a 9% reduction of total FODMAPs compared to the standard proofing, leading to 523 mg/100 g DM.

Ciabatta style breads

The results for the quantification of the FODMAP components in ciabatta style breads, produced with 90 min and 120 min proofing, are summarised in Table 8. Bread constituents, which act as FODMAPs are fructans, excess fructose and sorbitol. Furthermore, glucose and maltose were found in both breads as well, regardless of the length of fermentation. No detectable amounts of kestopentaose, kestose, nystose, stacyose, raffinose, sucrose, lactose or mannitol were identified in either of the ciabatta breads.

The predominant FODMAP components in the ciabatta breads are fructans. For the breads produced from standard and excessive proofing, the total fructan content was determined to 480 ± 11 mg/100 g DM and 436 ± 61 mg/100 g DM, respectively. The second most prominent FODMAP component in the breads was identified as fructose. Excess fructose was determined to 160 mg/100 g DM and 105 mg/100 g DM for the respective 90 min and 120 min proofed ciabatta breads. While the extended proofing has resulted in reductions in total fructans and excess fructose contents, the contrary became evident for sorbitol. Despite generally low amounts of sorbitol present in both breads, a significant increase from 45 ± 1 mg/100 g DM to 54 ± 1 mg/100 g DM was found as a result of the extended proofing. The concentrations of maltose and glucose did not change substantially due to the prolonged proofing time. However, the calculated total FODMAP content of the ciabatta breads was substantially lower in breads proofed for 120 min compared to 90 min proofing time. While standard proofing time of 90 min resulted in a total FODMAP content of 685 mg/100 g DM in the final bread, the proofing for 120 min reduced this value to 595 mg/100 g DM. This equals a reduction in total FODMAPs of 13% due to the prolonged proofing.

Effect of sourdough on FODMAPs in whole meal wheat breads

Whole meal and rye breads were, based on the flour analysis and existing literature [21, 28, 32], expected to contain particularly high FODMAP contents. The use of sourdough appears as a promising approach for the more efficient reduction of FODMAP compared to the prolonged proofing time. Therefore, practically relevant breads with and without the addition of sourdough were characterised for their FODMAP composition.

Table 9 Composition of relevant saccharides and polyols and total FODMAP content in whole meal wheat breads

	Fructan total ^a	Kestopen- taose ^b	Kestose ^b	Nystose ^b	Fructose ^b	Raffinose ^b	Sorbitol ^b	Mannitol ^b	FODMAP total ^c	Glucose ^b	Sucrose ^b	Maltose ^b
Whole meal wheat bread	552 ± 16	nd	nd	nd	2282 ± 88	nd	44 ± 1	33 ± 1	1860	1051 ± 5	nd	4331 ± 238
Whole meal wheat bread, sourdough	452 ± 45	nd	nd	nd	1752 ± 22	nd	56 ± 1	515 ± 14	1894	880 ± 13	nd	3562 ± 157

Results are given as (mg/100 g DM)

^aData were obtained by AOAC 999.03

^bData were obtained by HPAEC-PAD

^cFODMAP total = sum of fructans (including fructooligosaccharides), galactooligosaccharides (stachyose, raffinose), lactose, excess fructose and sugar polyols, nd: not detectable)

Addition of sourdough to wholemeal wheat breads

Neither of the breads contained substantial amounts of sucrose, raffinose, kestose, nystose and kestopentaose. On the other hand, maltose, glucose, fructose and FOS, as well as the polyols mannitol and sorbitol were found in both whole meal breads, regardless of the addition of sourdough.

The quantification of the components identified in the breads is summarised in Table 9. The main components identified are maltose, glucose and fructose. The fructose in excess of glucose was calculated to 1231 mg/100 g DM and 872 mg/100 g DM for the breads without and with sourdough, respectively. Furthermore, the level of total fructans (FOS) was determined to 552 ± 16 mg/100 g DM and 452 ± 45 mg/100 g DM for the breads without and with the addition of sourdough. This indicates a significant reduction of the total fructan contents as a result of the sourdough in the bread recipe. In contrast, the concentration of mannitol was substantially higher in the breads containing sourdough. While without sourdough a concentration of only 33 ± 1 mg/100 g DM was found, the mannitol content in the sourdough breads was determined to 515 ± 14 mg/100 g DM. Likewise, the amount of sorbitol was found to increase as a result of the sourdough addition but to a lesser extent.

Overall, the calculated total FODMAP content was not reduced due to the addition of sourdough to the bread recipe. While amounts of excess fructose and total fructans were reduced, the polyols mannitol and sorbitol were increased, leading to a different FODMAP composition but no changes in total FODMAP content.

Addition of sourdough to rye breads

Rye breads were prepared from refined (type 1150) and whole meal flour with the addition of sourdough, using three different processing options for each flour: Berlin short-term fermentation (BST), Detmolder one-step fermentation (D1S), Detmolder three-step fermentation (D3S). In none of the rye breads detectable amounts of kestose or raffinose were found. However, kestopentaose, nystose, fructose, sorbitol, mannitol and FOS were identified in all breads in varying concentrations. In addition, glucose, sucrose and maltose were found in each of the rye breads.

To evaluate the breads regarding their FODMAP composition, the concentrations of the different FODMAP components are summarised in Table 10.

First, substantial amounts of fructans were present in all rye breads but higher amounts were determined for the whole meal breads. It becomes evident that the D3S procedure results in slightly lower total fructan concentrations in the final breads compared to D1S. For D1S and D3S, total fructan concentrations were determined to 1712 ± 47 mg/100 g DM and 1698 ± 77 mg/100 g DM or

Table 10 Composition of relevant saccharides and polyols in rye breads and whole mal rye breads produced with different sourdough procedures

	Fructan total ^a	Kestopentaose ^b	Kestose ^b	Nystose ^b	Fructose ^b	Raffinose ^b	Sorbitol ^b	Mannitol ^b	FODMAP total ^c	Glucose ^b	Sucrose ^b	Maltose ^b
Rye bread type 1150 BST	1756 ± 65	32 ± 2	nd	44 ± 1	1028 ± 25	nd	122 ± 1	1162 ± 46	3039	1487 ± 26	21 ± 1	791 ± 23
Rye bread type 1150 D1S	1712 ± 47	35 ± 3	nd	42 ± 4	1265 ± 1	nd	125 ± 1	928 ± 2	2765	1292 ± 6	27 ± 1	447 ± 11
Rye bread type 1150 D3S	1698 ± 77	38 ± 1	nd	49 ± 1	1052 ± 18	nd	117 ± 1	1105 ± 1	2919	1377 ± 1	23 ± 1	566 ± 5
Whole meal rye bread BST	1936 ± 29	35 ± 4	nd	56 ± 3	935 ± 6	nd	127 ± 4	1420 ± 1	3483	1612 ± 4	8 ± 1	774 ± 63
Whole meal rye bread D1S	1944 ± 29	31 ± 1	nd	40 ± 1	751 ± 26	nd	115 ± 1	1208 ± 6	3267	1097 ± 2	10 ± 1	534 ± 6
Whole meal rye bread D3S	1914 ± 33	29 ± 1	nd	46 ± 2	648 ± 2	nd	111 ± 1	1532 ± 1	3557	1418 ± 3	11 ± 1	551 ± 2

Results are given as (mg/100 g DM)

BST Berlin short-term fermentation, D1S detmolder one-step fermentation, D3S detmolder three-step fermentation

^aData were obtained by AOAC 999.03

^bData were obtained by HPAEC-PAD

^cFODMAP total = sum of fructans (including fructooligosaccharides), galactooligosaccharides (stachyose, raffinose), lactose, excess fructose and sugar polyols, nd: not detectable

1944 ± 29 mg/100 g DM and 1914 ± 33 mg/100 g DM, using refined or whole meal flour, respectively. In addition, high levels of glucose and fructose were found in the rye breads. BST results in higher concentrations of glucose in the final breads, compared to D1S and D3S. For the whole meal breads in particular, it is evident that BST results, with concentrations of 1612 ± 4 mg/100 g DM and 935 ± 6 mg/100 g DM for glucose and fructose, in substantially higher monosaccharide concentrations compared to D1S with 1097 ± 2 mg/100 g DM and 751 ± 34 mg/100 g DM for glucose and fructose, respectively. However, due to the higher concentrations of glucose in all rye breads compared to the fructose concentration, no excess fructose is present in any of the breads. Hence, the fructose is not considered further for the evaluation of the breads regarding their FODMAP contents. The oligosaccharides kestopentaose and nystose were present only in relatively low concentrations of 30–40 mg/100 g DM and 40–60 mg/100 g DM, respectively. No significant changes in the concentration of these compounds could be found in relation to the type of rye flour or the sourdough procedure used. Likewise, sorbitol, which was detected in a range of 110–125 mg/100 g DM was not found to be affected substantially by the flour or sourdough procedure. The mannitol content was found to be generally higher in whole meal breads compared to the breads from refined rye flour. In particular for D3S, the mannitol concentration of the whole meal bread was with 1532 ± 1 mg/100 g DM substantially higher than in the corresponding bread made from refined flour (1105 ± 1 mg/100 g DM). Furthermore, it appears that the D1S led to lower amounts of mannitol in the bread compared with the other procedures for the same flour.

The calculated total FODMAP concentrations of the rye breads were found to range between 2765 and 3557 mg/100 g DM. Thereby, it is remarkable that the whole meal breads resulted in higher FODMAP contents than the T1150 breads, regardless of the procedure of sourdough implementation.

Discussion

FODMAPs of different flour types

Prior to the production of various practically relevant types of bread, the total FODMAP content and composition of the flours used were determined. These flours were the primary source of FODMAPs in the bread recipe. Hence, their composition gives valuable information for the subsequent evaluation of the breads, regarding the mechanisms behind a possible reduction of FODMAP content. The flours used here were whole meal and refined wheat and rye flour, respectively.

In good agreement with the results of Ziegler et al. [10], maltose, sucrose and glucose were the main saccharides

found in the wheat flours. In particular sucrose and maltose are not among the most commonly discussed FODMAPs but should not be left unconsidered. It was discussed in recent publications that these saccharides should be included in the concept of “new FODMAPs” [33, 34]. Deficiencies of brush border hydrolases can lead to these saccharides reaching the colon, where they are rapidly fermented by the gut microorganisms. The resulting symptoms are described as consistent with the malabsorption of carbohydrates [34]. Both wheat flours analysed showed substantial amounts of several FODMAP components, primarily branched and higher polymerised fructans (determined as total fructans due to a lack of authentic standards), but also nystose, kestopentaose, raffinose, fructose and sorbitol. None of the flours analysed contained excess fructose for further consideration in the evaluation of the FODMAP content. In general, the two rye flours were found to contain the same FODMAP components as the wheat flours, with the addition of sorbitol. Interestingly, the FODMAP concentrations of the refined and whole meal wheat flour were very different, in particular due to the higher amounts of fructans, raffinose and kestopentaose in the whole meal flour. However, also fructose, glucose and sucrose were substantially higher in the whole meal wheat flour. This is due to the highest concentration of fructans being located in the bran of wheat kernels [15]. The fructan concentrations in refined and whole meal wheat flours are comparable to previous findings [16]. Likewise, the galactosyl-oligosaccharide raffinose was, due to its predominant localisation in the wheat bran, found in significantly higher concentrations in the whole meal flour. In contrast, the concentrations of the FODMAP components analysed in the two rye flours showed much smaller differences. This indicates that with regards to FODMAPs it does not play an essential role if type 1150 rye flour or whole meal rye flour is used for the bread production. It is noteworthy, that sorbitol was only found in the rye flours, but not in either of the two wheat flours. In addition, both rye flours contained approximately double the amount of total FODMAPs compared to the whole wheat flour. Hence, the production of a low-FODMAP product from rye appears much more challenging than from wheat, regardless of the type of flour used. Primarily, this is a result of the substantially higher concentrations of oligosaccharides in the rye flours compared to wheat flours.

In general, the analytical results of the flours are in good agreement with the existing literature [10, 18, 35].

This is also consistent with the report of Gibson [36], indicating that rye causes stronger symptoms in IBS patients than wheat. Therefore, the use of refined wheat flour for the production of low-FODMAP breads and baking products appears the most logical approach. However, from a product variety and health benefit point of view, the use of other

types of flour should be encouraged. This would broaden the food selection available to IBS patients, allowing more variety to their restrictive diet. Furthermore, it would allow also IBS patients access to the proven health and gastro-intestinal benefits attributed to rye and whole meal products [36, 37].

Considering the low water content of the flours and the fact, that flour accounts for approximately 50% of the final breads, the need for fructan reduction strategies during bread making becomes evident. Without any reduction in total fructans, the resulting breads are likely to exceed the limit of 0.3 g of total oligosaccharides per serving [3].

According to [3, 5], one serving of bread equals 50 g.

Effect of proofing on FODMAPs

Due to the large variety of refined wheat breads with various processing conditions only incomplete data regarding the FODMAP content of the various types of bread is available. One of the processing parameters with the biggest impact on the FODMAP content of the final breads is expected to be the proofing time [10]. During proofing, the yeast in the dough actively metabolises dough constituents to grow and produce carbon dioxide, responsible for the rise of the dough in the oven. During this time substantial changes to the dough composition occur, which is also likely to affect the FODMAP components. Firstly, it is striking that compared to the wheat flours used to prepare the breads, no raffinose, kestopentaose or sucrose were found in the breads anymore. The degradation of these oligosaccharides by *S. cerevisiae* during proofing has been reported before [21]. In addition, the concentrations of the other FODMAP components identified in the bread are substantially reduced compared to the flour, showing the metabolic activity of the yeast. However, glucose and fructose are reduced to a much lower degree compared to the larger saccharides. The reason behind is that these are also substrates for the yeast and, therefore, not only released from the oligosaccharides but also simultaneously consumed by the yeast. In case of the maltose, even an increase as a result of the starch degradation during proofing was found.

In contrast, sorbitol was identified in all the breads although it was not present in the flour used for the preparation of these. Hence, it must be released by the yeast during proofing. Furthermore, the breads produced with a sourdough also contained mannitol. As this was only found in the breads produced with the addition of LAB, it can be concluded that these bacteria release the mannitol during the fermentation of the flour. This is also confirmed by previous reports [19, 38].

Furthermore, the results support the findings of Struyf et al. [21], that not all fructans are degraded equally. The authors reported, that fructans with a higher DP are not or much less efficiently degraded by the invertases released by

S. cerevisiae [21]. To achieve a more thorough degradation of fructans a yeast, such as *Kluyveromyces marxianus* would be needed [21, 28]. As a consequence, it was not possible to reduce the fructan content in breads from refined wheat flour below 180 mg/100 g DM.

For the ciabatta style breads, the FODMAP contents were generally higher compared to the other breads from refined wheat flour. This is a result of the addition of rye flour to the dough, which was shown to have higher FODMAP content than the wheat flours. The trend of the other breads was also confirmed here, showing that extended proofing time results in lower FODMAPs. However, both ciabattas were still higher in FODMAPs compared to the other breads from refined wheat flour. It also needs to be mentioned that the conditions during proofing of the ciabatta breads were slightly different. While all the other breads were proofed at 30 °C and 85% RH, the ciabattas were proofed at room temperature. Thus, the metabolic activity of the yeast was compromised resulting in the reduced degradation of fructans. Furthermore, at this temperature the yeast consumed less of the monosaccharides since it was less active. As a consequence, the fructose contents determined for the ciabatta breads are high as well.

The extended proofing significantly reduced the amount of glucose in the breads, causing a negative impact on the excess fructose. This is likely due to the increased consumption of the sugars by the yeast during the prolonged proofing of the dough.

Overall, a longer fermentation time decreased total FODMAP contents of the breads. This was particularly evident in the “standard” wheat breads.

Effect of sourdough addition

The implementation of a sourdough to wheat bread (60 min proofing time) was found to reduce the total fructan content of the breads, which is in good agreement with previous findings [19]. This is mainly due to the fermentation of the oligosaccharides by the lactic acid bacteria used as starter cultures [38]. On the other hand, lactic acid bacteria release polyols, which can induce IBS symptoms. Hence, the addition of sourdough did not substantially reduce the amount of total FODMAPs in the breads but alter the FODMAP composition. For the rye breads, no clear trend regarding the FODMAP content and composition could be found in relation to the sourdough preparation procedure. All the rye breads were very high in FODMAPs compared to the wheat breads, which agrees with the results of other researchers [3]. In similarity to the wheat breads, the use of whole meal flour resulted in higher total FODMAP content in the final bread. This is mainly due to the higher amounts of total fructans present in rye whole meal flour and bread. Furthermore, all the rye breads contained high amounts of mannitol,

which can be attributed to the sourdough fermentation by the lactic acid bacteria. In contrast to the whole meal wheat breads, no excess fructose was present in the rye breads, eliminating this saccharide as a FODMAP component. All six rye breads contained with more than 2500 mg/100 g DM much higher total FODMAP contents than all the wheat breads in this study. Only the implementation of sourdough was here not found to be a sufficient tool for the production of a low-FODMAP wholemeal wheat or rye bread. One of the reasons behind is the presence of *F. sanfranciscensis* as the only LAB strain in the commercial sourdough starter. Since this strain would primarily metabolise the fructose released from low DP fructans, while also producing mannitol it appears as sub-optimal solution for the low-FODMAP approach. Further investigations should, therefore, apply different strains, such as *L. plantarum* or *L. brevis*, to achieve a more efficient reduction in fructans and mannitol. Due to the necessity of sourdough to produce good quality rye breads the release of mannitol during bread making is a major challenge in low-FODMAP rye baking. Thus, further research activities should aim towards the selection of sourdough starter lactic acid bacteria, which can metabolise the FOS and GOS of the dough but have a low to non-existent release of polyols. Yet another approach worth of investigation is the use of alternative yeast strains to conventional baker's yeast, that can metabolise the released polyols, to produce a low-FODMAP product.

Comparison to low-FODMAP cut-off values

To classify the breads produced in this study as high- or low-FODMAP, the cut-off values determined by Varney et al. [3] were used. Therefore, the concentrations of total fructans (Fig. 1), mannitol (Fig. 2) and excess fructose (Fig. 3) were calculated, based on 50 g of fresh bread.

As can be seen from the Figures, all breads produced from wheat flour T550 can be classified as low-FODMAP, as they do not exceed any of the limits. In contrast, the breads from whole meal wheat flour and rye flour (T1150 and whole meal) are high-FODMAP products. For the whole meal wheat breads, excess fructose is the critical factor, exceeding the limitation for low-FODMAP products. It further can be seen clearly, that the use of sourdough reduced the excess fructose content but not enough to remain below the threshold, showing the limitations of the sourdough system applied here to produce low-FODMAP products. Further investigations should employ microbial cultures other than *F. sanfranciscensis* and *S. cerevisiae* to reduce the FODMAP content sufficiently.

The rye breads are exceeding the cut-off values for total fructans and mannitol. As a consequence, all rye breads of this study, independent from the type of flour and sourdough process applied, need to be classified as high-FODMAP products. Once again, this demonstrates the limitations of practically applicable processing conditions to reduce the

Fig. 1 Total fructan contents calculated per serve (50 g of fresh sample) of the wheat and rye bread samples in comparison to the cut-off value established by Varney et al. [3]. *BST* Berlin short-term sourdough, *D1S* detmold 1-step sourdough, *D3S* detmold 3-step sourdough

Fig. 2 Mannitol contents calculated per serve (50 g of fresh sample) of the wheat and rye bread samples in comparison to the cut-off value established by Varney et al. [3]. *BST* Berlin short-term sourdough, *D1S* detmold 1-step sourdough, *D3S* detmold 3-step sourdough

Fig. 3 Excess fructose contents calculated per serve (50 g of fresh sample) of the wheat and rye bread samples in comparison to the cut-off value established by Varney et al. [3]. *BST* Berlin short-term sourdough, *D1S* detmold 1-step sourdough, *D3S* detmold 3-step sourdough

FODMAP content. Hence, further investigations using alternative LAB as sourdough starters to prevent the excessive production of mannitol are required. Furthermore, the results demonstrate the need to find more efficient means of fructan reduction, to produce a low-FODMAP rye bread. As mentioned before, to date no study has reported a successful procedure to obtain a low-FODMAP rye bread. Hence, the application of alternative microbes in combination with further optimisation of the processing parameters is required.

Conclusions

In conclusion, this study has demonstrated that white wheat breads, produced under conditions similar to commercial breads can be considered as low FODMAP. All wheat breads from refined flour discussed in this section were found to remain below the cut-off values for low-FODMAP products previously published by Varney et al. [3]. Only the ciabatta style bread (prepared from wheat and rye flour) with 90 min proofing time had a concentration of fructans very close to the threshold of 0.2 g per serving (1 serving of bread = 50 g [5]). However, due to their health and dietary benefits, the consumption of rye and whole meal breads is recommended. Unfortunately, these breads were found to exceed the cut-off values for a low-FODMAP diet. Despite the possibility of a FODMAP reduction due to adjusted processing parameters, such as longer proofing times or the addition of sourdough, the whole meal rye breads were still not suitable for IBS patients. Therefore, it should be one aim of further research, to achieve a wholegrain/rye bread that is low in FODMAPs, to broaden the product variety available to IBS patients, as well as give them access to the nutritional and health benefits of whole meal bread.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Compliance with ethics requirements This article does not contain any studies with human or animal subjects.

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References

1. Yan YL, Hu Y, Gänzle MG (2018) Prebiotics, FODMAPs and dietary fiber—conflicting concepts in development of functional food products? *Curr Opin Food Sci* 20:30–37. <https://doi.org/10.1016/j.cofs.2018.02.009>
2. Oku T, Nakamura S (2002) Digestion, absorption, fermentation, and metabolism of functional sugar substitutes and their available energy. *Pure Appl Chem* 74(7):1253–1261. <https://doi.org/10.1351/pac200274071253>
3. Varney J, Barrett J, Scarlata K, Catsos P, Gibson PR, Muir JG (2017) FODMAPs: food composition, defining cutoff values and international application. *J Gastroenterol Hepatol* 32(Suppl 1):53–61. <https://doi.org/10.1111/jgh.13698>
4. Latulippe ME, Skoog SM (2011) Fructose malabsorption and intolerance: effects of fructose with and without simultaneous glucose ingestion. *Crit Rev Food Sci Nutr* 51(7):583–592. <https://doi.org/10.1080/10408398.2011.566646>
5. Heuer T, Krems C, Moon K, Brombach C, Hoffmann I (2015) Food consumption of adults in Germany: results of the German National Nutrition Survey II based on diet history interviews. *Br J Nutr* 113(10):1603–1614. <https://doi.org/10.1017/S0007114515000744>
6. Campbell JM, Bauer LL, Fahey GC, Hogarth A, Wolf BW, Hunter DW (1997) Selected fructooligosaccharide (1-kestose, nystose, and 1F-fructofuranosylnystose) composition of foods and feeds. *J Agric Food Chem* 45:3076–3082. <https://doi.org/10.1021/jf970087g>
7. Hamaker BR, Tuncil YE (2014) A perspective on the complexity of dietary fiber structures and their potential effect on the gut microbiota. *J Mol Biol* 426(23):3838–3850. <https://doi.org/10.1016/j.jmb.2014.07.028>
8. Henry RJ, Saini HS (1989) Characterisation of cereal sugars and oligosaccharides. *Cereal Chem* 66(5):362–365. ISSN: 0009-0352
9. Henry RJ (1987) Pentosan and (1→3), (1→4)-β-glucan concentrations in endosperm and wholegrain of wheat, barley, oats and rye. *J Cereal Sci* 6:253–258. [https://doi.org/10.1016/S0733-5210\(87\)80062-0](https://doi.org/10.1016/S0733-5210(87)80062-0)
10. Ziegler JU, Steiner D, Longin CFH, Würschum T, Schweiggert RM, Carle R (2016) Wheat and the irritable bowel syndrome—FODMAP levels of modern and ancient species and their

- retention during bread making. *J Funct Foods* 25:257–266. <https://doi.org/10.1016/j.jff.2016.05.019>
11. Murray K, Wilkinson-Smith V, Hoard C, Costigan C, Cox E, Lam C, Marciani L, Gowland P, Spiller RC (2014) Differential effects of FODMAPs (fermentable oligo-, di-, mono-saccharides and polyols) on small and large intestinal contents in healthy subjects shown by MRI. *Am J Gastroenterol* 109(1):110–119. <https://doi.org/10.1038/ajg.2013.386>
 12. Verspreet J, Dornez E, Van den Ende W, Delcour JA, Courtin CM (2015) Cereal grain fructans: structure, variability and potential health effects. *Trends Food Sci Technol* 43(1):32–42. <https://doi.org/10.1016/j.tifs.2015.01.006>
 13. Verspreet J, Pollet A, Cuyvers S, Vergauwen R, Van den Ende W, Delcour JA, Courtin CM (2012) A simple and accurate method for determining wheat grain fructan content and average degree of polymerization. *J Agric Food Chem* 60(9):2102–2107. <https://doi.org/10.1021/jf204774n>
 14. Costantini A, Amoriello T, Cecchini C, D'Egidio MG, (2007) Analysis of factors influencing fructans production in winter cereals. *J Genet Breed* 62(1):15–24
 15. Haskå L, Nyman M, Andersson R (2008) Distribution and characterisation of fructan in wheat milling fractions. *J Cereal Sci* 48(3):768–774. <https://doi.org/10.1016/j.jcs.2008.05.002>
 16. Huynh B-L, Palmer L, Mather DE, Wallwork H, Graham RD, Welch RM, Stangoulis JCR (2008) Genotypic variation in wheat grain fructan content revealed by a simplified HPLC method. *J Cereal Sci* 48(2):369–378. <https://doi.org/10.1016/j.jcs.2007.10.004>
 17. Knudsen KEB (1997) Carbohydrate and lignin contents of plant materials used in animal feeding. *Anim Feed Sci Technol* 67:319–338. [https://doi.org/10.1016/S0377-8401\(97\)00009-6](https://doi.org/10.1016/S0377-8401(97)00009-6)
 18. Karpinen S, Myllymäki O, Forsell P, Poutanen K (2003) Fructan content of rye and rye products. *Cereal Chem* 80(2):168–171. <https://doi.org/10.1094/CCHEM.2003.80.2.168>
 19. Lopenen J, Ganzle MG (2018) Use of sourdough in low FODMAP baking. *Foods*. <https://doi.org/10.3390/foods7070096>
 20. Whelan K, Abrahamsohn O, David GJ, Staudacher H, Irving P, Lomer MC, Ellis PR (2011) Fructan content of commonly consumed wheat, rye and gluten-free breads. *Int J Food Sci Nutr* 62(5):498–503. <https://doi.org/10.3109/09637486.2011.553588>
 21. Struyf N, Laurent J, Verspreet J, Verstrepen KJ, Courtin CM (2017) *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* cocultures allow reduction of fermentable oligo-, di-, and mono-saccharides and polyols levels in whole wheat bread. *J Agric Food Chem* 65(39):8704–8713. <https://doi.org/10.1021/acs.jafc.7b02793>
 22. Knez M, Abbott C, Stangoulis JCR (2014) Changes in the content of fructans and arabinoxylans during baking processes of leavened and unleavened breads. *Eur Food Res Technol* 239(5):803–811. <https://doi.org/10.1007/s00217-014-2273-1>
 23. Nilsson U, Öste R, Jägerstad M (1987) Cereal fructans: hydrolysis by yeast invertase, in vitro and during fermentation. *J Cereal Sci* 6:53–60. [https://doi.org/10.1016/S0733-5210\(87\)80040-1](https://doi.org/10.1016/S0733-5210(87)80040-1)
 24. Brandt MJ (2007) Sourdough products for convenient use in baking. *Food Microbiol* 24(2):161–164. <https://doi.org/10.1016/j.fm.2006.07.010>
 25. Brandt MJ, Gänzle M (2006) *Handbuch Sauerteig*. Behr's Verlag, Hamburg. ISBN: 978-3-89947-166-3
 26. Ganzle M, Ripari V (2016) Composition and function of sourdough microbiota: from ecological theory to bread quality. *Int J Food Microbiol* 239:19–25. <https://doi.org/10.1016/j.ijfoodmicro.2016.05.004>
 27. De Vuyst L, Harth H, Van Kerrebroeck S, Leroy F (2016) Yeast diversity of sourdoughs and associated metabolic properties and functionalities. *Int J Food Microbiol* 239:26–34. <https://doi.org/10.1016/j.ijfoodmicro.2016.07.018>
 28. Struyf N, Vandewiele H, Herrera-Malaver B, Verspreet J, Verstrepen KJ, Courtin CM (2018) *Kluyveromyces marxianus* yeast enables the production of low FODMAP whole wheat breads. *Food Microbiol* 76:135–145. <https://doi.org/10.1016/j.fm.2018.04.014>
 29. Pejcz E, Spychaj R, Gil Z (2020) Technological methods for reducing the content of fructan in rye bread. *Eur Food Res Technol* 246(9):1839–1846. <https://doi.org/10.1007/s00217-020-03537-5>
 30. Science IafC (1976) Technology ICC Standard No. 110/1, Determination of the Moisture Content of Cereals and Cereal Products (Practical Method). ICC, Vienna
 31. Gibson PR, Newnham E, Barrett JS, Shepherd SJ, Muir JG (2007) Review article: fructose malabsorption and the bigger picture. *Aliment Pharmacol Ther* 25(4):349–363. <https://doi.org/10.1111/j.1365-2036.2006.03186.x>
 32. Biesiekierski JR, Rosella O, Rose R, Liels K, Barrett JS, Shepherd SJ, Gibson PR, Muir JG (2011) Quantification of fructans, galacto-oligosaccharides and other short-chain carbohydrates in processed grains and cereals. *J Hum Nutr Diet* 24(2):154–176. <https://doi.org/10.1111/j.1365-277X.2010.01139.x>
 33. Gibson PR, Halmos EP, Muir JG (2020) Review article: FODMAPs, prebiotics and gut health-the FODMAP hypothesis revisited. *Aliment Pharmacol Ther* 52(2):233–246. <https://doi.org/10.1111/apt.15818>
 34. Halmos EP, Gibson PR (2019) Controversies and reality of the FODMAP diet for patients with irritable bowel syndrome. *J Gastroenterol Hepatol* 34(7):1134–1142. <https://doi.org/10.1111/jgh.14650>
 35. Ispiryani L, Zannini E, Arendt EK (2020) Characterization of the FODMAP-profile in cereal-product ingredients. *J Cereal Sci*. <https://doi.org/10.1016/j.jcs.2020.102916>
 36. Gibson PR (2017) History of the low FODMAP diet. *J Gastroenterol Hepatol* 32(Suppl 1):5–7. <https://doi.org/10.1111/jgh.13685>
 37. Laatikainen R, Koskenpato J, Hongisto SM, Lopenen J, Poussa T, Hillilä M, Korpela R (2016) Randomised clinical trial: low-FODMAP rye bread vs. regular rye bread to relieve the symptoms of irritable bowel syndrome. *Aliment Pharmacol Ther* 44(5):460–470. <https://doi.org/10.1111/apt.13726>
 38. Gänzle MG (2015) Lactic metabolism revisited: metabolism of lactic acid bacteria in food fermentations and food spoilage. *Curr Opin Food Sci* 2:106–117. <https://doi.org/10.1016/j.cofs.2015.03.001>

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