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Title	Impact of different <i>S-cerevisiae</i> yeast strains on gluten-free dough and bread quality parameters
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18 **Abstract**

19 Yeasts have been used for centuries for the leavening of bread. The main emphasis on the selection of
20 yeast strains has been in relation to wheat products. This study is the first evaluation of different yeasts
21 coming from the baking and brewing industry in a gluten-free system. Five different yeast strains (US-
22 05, WB-06, T-58, S-23, Baker's yeast) of the species *Saccharomyces cerevisiae* were evaluated for
23 their suitability to leaven gluten-free dough. A wide range of dough quality characteristics such as the
24 time and temperature-dependent rising behaviour, the chemical composition of the dough and the pH
25 were determined. In addition to this, the bread quality attributes like, volume, texture, structure, aroma
26 and flavour were evaluated. Obtained results indicated different activity levels between the selected
27 yeast strains. Doughs prepared with US-05 showed a slower dough rise during proofing and a decreased
28 height, in comparison to the Baker's yeast control. The application of WB-06 and T-58 however,
29 resulted in a faster dough rise and increased dough height with greater gas cells ($p < 0.05$). These
30 observations were also found in the baked breads, where these two yeasts reached a higher specific
31 volume and a softer breadcrumb than the Baker's yeast bread ($p < 0.05$). Statistical analysis revealed
32 strong correlations ($p < 0.05$) between activity level, dough properties and bread properties. Results
33 obtained showed that the selected yeast strains reached different level of activity due to diverse
34 preferences in temperature, time and sugars. Yeast strains which originated from the brewing industry
35 performed were found to be suitable for gluten-free breadmaking.

36

37 **Keywords:** Dough-rise, beer yeast, starch-based system, fermentation

38

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44

46 The preparation of bread by yeast fermentation is one of the oldest biochemical processes in the world
47 [1]. *Saccharomyces cerevisiae* (or Baker's yeast) is the commonly used yeast, which is the primary
48 leavening agent in bread products [2]. Fermentation plays a key role in the breadmaking process, as it
49 can improve texture, structure, taste and flavour in the final product [2]. In recent years the effect of
50 yeast modification and replacement by alternative yeast strains in the bread baking process has become
51 a topic of interest. Studies focused on the harvesting time of Baker's yeast at different physiological
52 phases [3] or the replacement of Baker's yeast by beer yeasts [4]. Beer yeast strains are known to have
53 optimized metabolism suitable for beer making in terms of flavour compounds and alcohol production.
54 On the other hand, Baker's yeast focuses on a fast fermentation and uniform dough leavening due to
55 carbon dioxide production [5]. Studies by Heitmann et al. [4, 6] demonstrated that the use of different
56 *Saccharomyces cerevisiae* strains showed significant differences to the commonly applied Baker's
57 yeast in wheat bread. It also was found that brewer's yeast can improve quality parameters like the
58 texture, structure and the aroma profile of bread.

59 However, people who suffer from coeliac disease or other gluten-related disorders cannot consume
60 these products. For these individuals, a gluten-free diet is currently the only treatment for these disorders
61 [7]. A recent study by Tsatsaragkou et al. [8], stated that the gluten-free bread market still faces the
62 main challenges of improving technological quality parameters bread technology quality, an extension
63 of shelf life and a balanced nutritional value. The application of different yeast strains from the brewing
64 and baking industry in gluten-free breads is a novel approach. It is believed that the different strains
65 influence the final gluten-free bread properties due to different gas cell expansion and interactions. Not
66 only the influence on the dough and bread parameters but also aroma and flavour profile of breads can
67 be influenced by the application of different yeasts and their individual fermentation process [9].
68 Bircher et al. [10] identified a wide range of aroma active volatiles within the yeast metabolism. The
69 change of this flavour and aroma profiles, using different yeasts has become a further topic of
70 commercial interest. Since some of the aroma profiles are considered as quality parameters for bread
71 products [10-12]. Especially, the aroma and flavour profiles of gluten-free breads are still considered
72 as improvable by the consumers. Hence, the modification of these profiles by the application of different
73 yeasts could improve the perception and acceptance of gluten-free products.

74 To the authors knowledge, this study is the first study to apply different yeast strains which are
75 commonly used in the brewing industry in a gluten-free bread system. During the fermentation process
76 yeast produces mainly carbon dioxide and ethanol, but also secondary metabolites, such as glycerol,
77 organic acids and flavour compounds which have an impact on the final product quality [13]. The
78 effects of yeast on bread quality characteristics include the volume, structure, flavour and shelf life of
79 each fermented product [2]. Based on the specific characteristics of various *S. Cerevisiae* yeast strains,
80 the authors believe that their application will have significant influence on final gluten-free bread
81 quality (Table 1). The main differences between the yeast strains are the optimum temperatures and
82 their different tolerances to temperature changes. The optimal temperature for Baker's yeast is higher
83 than in comparison to the beer yeasts. Despite the lower optimum temperatures for the yeast strain S-
84 23 and T-58 for fermentation. These two strains are described to have a faster fermentation at higher

85 temperatures, which are close to the optimum temperature of Baker's yeast. A further important
86 characterising of yeasts is the metabolism of different sugars of the various yeasts. Especially in a very
87 refined system such as that of a gluten-free formulation, sugar sources are limited and usually
88 constructed of mainly complex sugars. These sugars are usually only accessible to yeast fermentation
89 when degraded by enzymes to smaller fermentable sugars. The gluten-free system in this study creates
90 such case which consists of limited amounts and varieties of sugar and further does not contain added
91 enzymes for the breakdown of the complex sugars. The main component in the system is potato starch,
92 which consists of about 92% total starch, 1% damaged starch, 0.02% protein and no lipids. Additionally,
93 no enzyme activity (α - and β -amylase) was determined in this potato starch. This gluten-free bread
94 system is very refined and does not offer as many nutrients for yeast metabolism as the conventional
95 wheat bread system. However, effects on the gluten-free bread quality parameters by the application of
96 the various yeasts was expected. Therefore, five yeast strains of the *S. cerevisiae* family namely US-05,
97 T-58, S-23, WB-06 and a control Baker's yeast have been selected and their effect on dough and final
98 bread quality have been analysed. This study will broaden the understanding of the yeast on gluten-free
99 dough characteristics, bread quality parameters and sensory attributes.

100

101

102 **2. Experimental**

103 **2.1 Materials**

104 Potato starch was supplied by Emsland, Germany; pea protein by Roquette, France; pectin by Cp Kelco,
105 Germany; sugar by Siucra Nordzucker, Ireland; salt by Glacia British Salt Limited, UK. Instant active
106 dry Baker's yeast was obtained from Puratos, Belgium; Dry yeast s-23, T-58, us-05 and wb-06 were
107 supplied by Fermentis Division of S. I. Lesaffre, France. All the yeasts applied in this study belonged
108 to the species *S. cerevisiae*. All chemicals were supplied by Sigma-Aldrich, Arklow, Ireland.

109 **2.2 Compositional analysis**

110 The total starch content of potato starch was determined according to AACC Method 76-13.01. The
111 alpha (AACC Method 22-02.01) and beta (K-BETA3) amylase activity were determined using
112 commercially available enzyme kits, supplied by Megazyme, Ireland. The total nitrogen content of the
113 starch sample was determined according to the Kjeldahl method (MEBAK 1.5.2.1). To convert the
114 nitrogen content into the protein content the factor of 6.25 was used. The air oven method (AACC
115 Method 44-15A) was applied to determine the moisture content of the samples. The determination of
116 the lipid content was performed according to the Soxlet-method (AACC Method 30-25.01) with a pre-
117 digestion of the samples in HCl, to release bound lipids.

118 **2.3 Cell count**

119 Cell viability (cfu/g) of the yeast powders, was analysed by suspending 1 g freeze-dried yeast in 10 mL
120 distilled water. From this stock solution, serial dilutions were prepared with ringer solution and spread
121 on malt extract agar (Merck, Germany) plates and incubated aerobically for 2 days at 25°C. Plates with
122 30 to 300 colonies were selected for yeast cell counts.

123 **2.4 Total available carbohydrates**

124 The total available carbohydrate level from freeze-dried dough and breadcrumb samples was
125 determined spectrophotometrically by using an enzyme kit (K-TSTA) supplied by Megazyme, Ireland.
126

127 **2.5 Sugars and acids**

128 Sugar levels of dough and breadcrumb were analysed for glucose and fructose by an Agilent 1260 high-
129 performance liquid chromatography system (HPLC) with a Hi-Plex H+ column (Agilent, Cork, Ireland)
130 coupled to a refractive index detector (RID) at 35 °C. The sugars were extracted with distilled water for
131 20 min under shaking and then centrifuged at 3000g for 10 minutes. The HPLC analysis was performed
132 at 30 °C column temperature with water (HPLC-grade) at a flow rate of 0.6 mL/min. The analysis of
133 citric acid, succinic acid and acetic acid were analysed with the same system but small modifications.
134 A Diode-Array Detection (DAD) and the HiPlex H+ Column at 65 °C were used to detect the acids.
135 Samples were eluted with 0.005 M H₂SO₄ at a flow rate of 0.5 mL/min.

136 **2.6 Dough and bread crumb pH measurement**

137 Dough pH before and after proofing was measured according to the AACC method 02-52.

138 **2.7 Time- and temperature-dependent rising behaviour of dough**

139 The measurements were conducted using an Anton Paar MCR rheometer with the TruStrain™ option.
140 A confined measuring system (CMS) was placed on the inset plate (I-PP25) of a plate-plate system
141 (Figure 1b). The CMS is a stainless-steel cylinder with the height of 33 mm and the inner diameter of
142 25 mm. A Peltier temperature device (PTD) was used as well as a convention temperature device (CTD)
143 for temperature control (Figure 1b). To mimic the proofing properties the PTD was set at 30°C for 45
144 min with a constant normal force (FN) was set to 0.0 to ensure permanent contact between sample and
145 upper plate. For determination of the oven spring and the determination of yeast activity during the
146 baking process the temperature was increased to 90°C with a heat rate of 4°C /min. Recorded and
147 calculated parameters were the max height [mm], which is the maximum height the dough reached
148 during the measurement. Further the slope during the fermentation process (Slope 30°C) and then
149 during the baking process (Slope 90°C) for determination of yeast activity was calculated. Also, the
150 max height temperature (TMH) [°C] was recorded and used as an indicator for the heat tolerance of the
151 various yeasts.

152 **2.8 Bread production**

153 Bread samples were prepared according to Horstmann et al. [14]. The formulation of the various breads
154 included: 2% pectin, 2% pea protein, 2% salt, 4% sugar, 75% water based on starch weight. Amounts
155 of yeasts were added according to their cell viability (Table 2). Dry ingredients were mixed and yeast
156 was suspended in warm water (27°C) and regenerated for a period of 10 min. Mixing was carried out
157 with a k-beater (Kenwood, Havant, UK) at low disk speed (level 1 of 6) for 1 minute in a Kenwood
158 Major Titanium kmm 020 Mixer (Kenwood, Havant, UK). After the first mixing, the dough was scraped
159 down from the bowl walls. A second mixing step of 2 minutes at higher disk speed (level 2 of 6) was
160 applied. 300g of batter were weighed into baking tins of 16,5 cm x 11 cm x 7 cm and placed in a proofer

161 (KOMA, Netherlands) for 45 min at 30°C and 85% relative humidity (RH). The proofed samples
162 were then baked for 45 min at 220°C top and bottom heat in a deck oven (MIWE, Germany), previously
163 steamed with 0.4 L of water. The breads were cooled for 2 hours prior to analysis.

164 **2.9 Bread analysis**

165 The specific volume of the bread was determined by use of a Vol-scan apparatus (Stable Micro System,
166 UK). The specific volume is calculated on the basis of loaf volume and weight. An image analysis
167 system (Calibre Control International Ltd., UK) was used to analyse the breadcrumb structure, chosen
168 parameters were the cell diameter and the number of cells per slice area. Crumb firmness was analysed
169 using a Texture Profile Analyser (TA-XT2i, Stable Micro Systems, Godalming, England) with a 25 kg
170 load cell, which compresses the breadcrumb with a 20 mm aluminium cylindrical probe. Bread samples
171 were sliced into 20 mm slices and analysed with a test speed of 5 mm/s and a trigger force of 20 g,
172 compressing the middle of the breadcrumb to 10 mm. The measurement with the various parameters
173 was conducted on the baking day and 24h after baking to monitor the staling process. Baked breads
174 were stored in polythene bags (polystyrol-ethylene veniyl alcohol-polyethylene).

175 **2.10 Extraction of Volatile Aroma Compounds by Thermal Desorption (TD) and Quantification** 176 **using GC-MS**

177 To extract volatile compounds, samples were prepared by weighing 0.1g of bread crumb into a clean
178 glass thermal desorption (TD) tube to concentrate the volatile aroma compounds in a gas stream prior
179 to injection (Perkin Elmer Turbomatrix 650). Subsequently, the aroma compounds were absorbed at
180 90°C for 10 min. For the quantification of the aroma-active volatiles, a gas chromatography-mass
181 spectrometer (GC-MS, Agilent 5977B MSD) with a Rxi 624-Sil 20m column and helium as a carrier
182 gas was used. The details for the temperature profile are: start temperature: 35°C (4 min) with an
183 increase of 15°C/min to 220°C (hold 1 minute). The total run time was 17.3 min. For the detected
184 compounds a database search was conducted. The aroma compounds detected and analysed in this study
185 by GC-MS TD were ethanol, acetic acid, 2,3-butandiol and 1-hydroxy-2-propanone.

186 **2.11 Sensory Analysis**

187 Aroma profile analysis on bread samples was performed by a trained panel (training over 2 weeks based
188 on reference sample) consisting of 10 panellists. Training began by generating a consensus vocabulary
189 for attributes and descriptors based on the control sample. The sensory evaluation was performed by
190 each panellist individually in an isolated booth. All trainings and sensory analyses were performed in a
191 sensory panel room at 21 +/- 1°C. Agreed descriptors are listed in Online resource 1. For the descriptive
192 aroma profile, each breadcrumb sample was cut into slices (thickness 2cm) and presented to panellists
193 90 minutes after baking. The sensory scale was based on an unstructured line scale to describe the
194 intensity of rated sensory attributes.

195 **2.12 Statistical analysis**

196 All measurements were performed at least in triplicate. The significance of the results was analysed
197 using One Way ANOVA (R version 3.0.1). The level of significance was determined at $p < 0.05$. In
198 addition, Pearson correlation analysis (R version 3.0.1) was applied to find correlation between yeast
199 properties and the results of the baked products.

200 **3. Results and Discussion**

201 **3.1 Cell Count**

202 The viability of freeze-dried yeast cells was analysed to standardise the inoculum level of yeast for the
203 baking of the various breads. The control yeast *S. cerevisiae* Baker's yeast had a cell count of $1.06E +$
204 09 cfu/g. The beer yeasts showed lower cell count in decreasing order: *S. cerevisiae* WB-06 $7.16E +08$
205 cfu/g; *S. cerevisiae* T-58 $5.5E +08$ cfu/g; *S. cerevisiae* S-23 $5.18E +08$ cfu/g and *S. cerevisiae* US-05
206 $4.74E +08$ cfu/g. Comparable results were found by Heitmann et al. [4]. The addition levels of the yeast
207 in the dough formulation were based on the concentration usually reached by the control yeast (*S.*
208 *cerevisiae* Baker's yeast) (Table 1). When dried yeasts are used in bread the non-viable cells need to be
209 considered, since non-viable cells can release glutathione as a stress response [15-17]. In wheat doughs,
210 the release of glutathione has a strong reducing effect which ultimately leads to a modification of the
211 viscoelastic gluten network [16, 18]. Glutathione was further applied in a gluten-free formulation and
212 found to improve rice-flour based bread quality parameters [19]. The analysed bread system showed
213 interactions between glutathione and the rice protein 'glutelin' resulted in an improvement of the
214 volume and crumb structure of the bread. However, based on the lack of gluten, rice flour and glutelin
215 in the used formulation in this study, the effect of glutathione on bread parameters was neglected.

216 **3.2 Total starch**

217 The total starch content of the doughs and breads was analysed to identify difference in the yeast
218 performance. No significant differences between the total starch contents in the dough were found
219 (Table 2). However, differences in the starch content of the final breads were detected. This indicates
220 different activities of the various yeast strains during processing. Breads baked with the *S. cerevisiae*
221 strains T-58 (75.97%) and S-23 (78.57%) showed the significant lowest amount of total starch. The
222 control baked with *S. cerevisiae* Baker's yeast had the significant highest amount of total starch left
223 (87.27%), suggesting a lower activity. Heitmann et al. [4] analysed the application of beer yeast strains
224 in wheat bread and also found Baker's yeast to have the highest amount of starch left in the final bread.
225 The authors mentioned that the lower content of total starch in the breads prepared with beer yeast
226 resulted from their higher enzyme activities in comparison to Baker's yeast, which degrade starch into
227 more fermentable sugars [20]. The values in the study by Heitmann et al. [4] showed lower total starch
228 values, which is explained by the higher concentration of starch in this study as explained earlier in the
229 introduction.

230 **3.3 Sugars and Acids**

231 The analysis of fermentable sugars like glucose and fructose showed fluctuation and significant
232 differences amongst the different yeasts (Table 3). All the yeasts showed a decrease in glucose and
233 fructose after baking, confirming that all the yeast strains have metabolic activity. The sugar contents
234 in the final bread of fructose and glucose showed the lowest values in the formulations with the addition
235 of T-58, suggesting a higher activity in comparison to the other yeasts. This functionality is
236 hypothesised by the authors to be the result of the higher temperature tolerance and fast fermentation at
237 higher temperatures in comparison to the remaining yeast strains (Table 1). It is well known that yeast
238 activity can be influenced by many factors such as the pre-growth conditions of yeast, dough
239 fermentation conditions, dough ingredients and the genetic background of the various yeast strains [21].
240 The acid analysis (citric acid, succinic acid, lactic acid, acetic acid) of the dough and bread samples
241 formulated with the different yeasts did not find detectable quantities. Only quantities of acetic acid
242 were found in bread samples as part of volatile compound analysis (Table 4). The detection of acetic
243 acid during the volatile compound analysis is explained by the different detection limits of the two used
244 detection methods. GC-MS used for the volatile compound analysis can detect compounds in ppm
245 quantities while the detection limit of the HPLC is significantly higher. Acetic acid values measured by
246 the GC were observed to be four times higher in bread crumbs baked with *S. cerevisiae* S-23 in
247 comparison to the remaining yeasts. The lowest value was found in breadcrumbs of breads baked with
248 US-05, which overall showed low amounts of volatile compounds. Acetic acid contributes to the overall
249 aroma of baked goods [22]. Its organoleptic descriptors are vinegar, pungent and sour, hence the
250 differences in the amounts of acetic acid are assumed to influence the sensory evaluation. These small
251 quantities however are not considered to affect the dough and bread properties or to contribute to the
252 flavour or aroma profile. Based on the refined gluten-free system in this study in addition to the limited
253 amount of oxygen in a dough system, the acid analysis suggests that the metabolic pathways of the
254 various yeasts followed the alcoholic fermentation, rather than the TCA cycle [6]. As discussed earlier,
255 the refined system was considered to not provide enough nutrients for the yeast to synthesise
256 metabolites like acids.

257 **3.4 pH values**

258 Changes in pH of the dough before and after proofing and in the final bread are shown in Table 2. The
259 various *S. cerevisiae* yeast strains showed significant differences in the pH development over the
260 breadmaking process. Overall it was observed that the doughs decreased in pH during fermentation and
261 increased after baking. US-05 and S-23 had the significant highest pH before proofing. Doughs
262 formulated with *S. cerevisiae* T-58 showed the significant lowest pH. Also, after proofing T-58 showed
263 the lowest and US-05 the highest pH. The effect of acids on pH in this study was excluded since they
264 were not detected. Thus, the effect of CO₂ production is assumed to be the main cause for the changes
265 in pH [23]. After the baking process, an increase in the pH values in all the baked breads was observed.
266 Even though the pH increased, the lowest pH was found for breads formulated with T-58. The
267 significant highest pH value was reached by breads containing the yeast strain WB-06 followed by US-
268 05. The effect of the pH increase after baking is explained by the loss of carbon dioxide and linked
269 carbonic acid. Reduction in pH indicates CO₂ and ethanol production by the yeasts. The more active

270 the yeasts the more sugars are fermented, and the more CO₂ is produced, dropping the pH in the dough
271 [24].

272 **3.5 Time- and temperature- dependent rising behaviour of dough**

273 The evaluation of dough rising behaviour is a commonly determined parameter in wheat-doughs, to
274 achieve constant dough quality. The measurement is usually conducted with the aid of the
275 rheofermentometer. This machine, however, showed limitations in analysing gluten-free batters due to
276 their liquid nature.

277 Therefore, a new method was established using the Anton paar® rheometer attached with the
278 TruStrain™ system, allowing the determination of the dough rise and providing a prediction tool for
279 yeast activity (Figure 1). Analysed parameters were the max height, the slope during the fermentation
280 process (Slope 30°C), the baking process (Slope 90°C) and max height temperature (TMH) (Table 2).
281 It was found that doughs formulated with *S. cerevisiae* T-58 had the highest dough rise in comparison
282 to the other strains. The lowest dough rise was observed for US-05. The temperature at which the
283 maximum height was reached indicates that the control yeast reached its maximum height significantly
284 earlier than the remaining yeasts. The yeast strains S-23 and WB-06 reached their maximum height at
285 significantly higher temperatures. The different temperatures to reach the max height are not correlated
286 but can be explained by the different activities of the yeast strains and their preferred temperatures
287 (Table 1) [25]. The slope during the fermentation phase (FP) at 30°C presented T-58 as the most active
288 yeast with a slope twice as high as the control, which is the second most active strain. The authors
289 hypothesise that this high activity is the result of the temperature optimum for fast fermentation (32
290 °C). The explanation why S-23 and WB-06 reached a higher height than the control is due to their
291 increase in activity at higher temperatures (Slope BP). This high increase would suggest a more
292 pronounced oven spring as usually observed during the baking process. The differences in the optimal
293 fermentation temperatures and metabolism of sugar affected the chemical and technological properties
294 of the gluten-free dough. When optimal conditions are provided, yeast can work at its full potential.
295 This was confirmed by reduced levels of sugars in the final bread and the pH development of the bread
296 making process. Correlation analysis revealed strong negative correlations between the pH and dough
297 rise ($r = 0.921$, $p < 0.001$). The correlation is explained by the produced CO₂, which is decreasing the pH
298 due to its carbonic acid and the expansion of gas cells accelerating the dough rise [4, 23]. The production
299 of CO₂ is considered as an indicator for yeast activity [4]. The more CO₂ and ethanol are produced by
300 yeast, the more active it is considered. The differences in the activity between the various yeast strains
301 can be explained by the negative correlations between the remaining sugars in the final bread and the
302 dough rise ($r = -0.879$, $p < 0.001$). This is due to the metabolism of the different yeasts, which ferment
303 the available sugars and produces CO₂ [13]. The more sugars are fermented the more CO₂ is produced
304 and the higher is the dough rise. Overall the method showed similarities to rheofermentometer results
305 found by Heitmann et al. [4], who applied beer yeast strains to wheat breads. In their study, it was also
306 observed that T-58 had the highest activity and US-05 the lowest which was explained by a slower
307 fermentation of sugars. The obtained results of the various yeast strains show the suitability of the

308 method for gluten-free doughs. It is further hypothesised that it can be used as an indicator for the final
309 bread properties.

310 **3.6 Bread results**

311 One of the most important quality parameters and the first impression for the consumer is the
312 appearance of a product. Figure 2 illustrates cross sections and surface images of the baked breads with
313 the different yeasts. It can be observed, that breads baked with the ale yeast US-05 showed reduced loaf
314 volume and smaller average cell pore size. Bread baked with WB-06 and S-23 showed a closer
315 resemblance to the control bread in terms of size and cell pore size. The effect of T-58, however, showed
316 a bigger loaf volume and big gas cells in comparison to the control bread (Baker's yeast). A more
317 detailed description of the quality parameters is presented in Table 3. The images of the breads
318 containing the different yeasts depicted in Figure 2 indicate significant differences between the bread.
319 The specific volume and its related appearance is the most important bread quality parameter which has
320 a high influence on the consumers quality perception [27]. The differences of the specific volume are
321 significant and show the breads baked with T-58 showed the highest loaf volume (Table 3). The other
322 applied yeasts either had no significant differences (WB-06) or resulted in inferior bread characteristics
323 (S-23, US-05) particularly relating to the volume of the breads. Next, to the influence of the yeast, a
324 key role for the rise of a bread is the dough consistency. After mixing and heating, the dough can
325 facilitate the entrapment of produced gas and the expansion of the gas cells [28]. The cell structure of
326 bread is a key quality criterion which can be related to crumb hardness and the specific volume. The
327 development of crumb structure and gas cells expansion initially starts during fermentation, when CO₂
328 and ethanol are produced as products of the yeast metabolism. In the baking process then the produced
329 ethanol evaporates with some of the water and helps the expansion of gas cells and ultimately the loaf
330 rise [23]. Cell structure of bread is a key quality criterion which can be related to crumb hardness and
331 the specific volume. Parameters chosen for the crumb structure were the number of cells, cell diameter
332 and the number of cells per slice area. The application of the ale yeast US-05 was the only yeast which
333 increased the number of cells significantly in comparison to the baker's yeast (control). The addition of
334 the remaining yeast led to breads with a lower number of cells when compared to the control. The
335 combination of the number of cells and their development of crumb structure and gas cells expansion
336 initially starts during fermentation, when CO₂ and ethanol are produced as products of the yeast
337 metabolism. In the baking process then the produced ethanol evaporates with some of the water and
338 helps the expansion of gas cells and ultimately the loaf rise [23]. This explains the results of breads
339 baked with US-05, which despite their high number of cells, but because of their small crumb cell
340 diameter led to small loaf volume. The opposite effect was found in breads containing T-58. The breads
341 showed the lowest number of cells; however, these cells showed the significant highest cell diameter
342 resulting in breads with the significant highest specific volume (Table 3). The number of cells / slice
343 area (mm²) gives the ratio of cells per mm² on the bread. Breads baked with US-05, S-23 showed the
344 highest ratio in comparison to the control. No significant differences were found between WB-05 and
345 the control. The significant lowest value was found in breads baked with T-58. Texture is a further
346 important quality characteristic for consumer acceptance [25]. The process of increasing hardness over

347 time is known as staling and has been claimed to affect the flavour of a bread [29]. Hardness of the
348 breadcrumb was chosen to determine textural parameters. The hardness was measured 2h and 24h after
349 baking. Both measurements of hardness showed significant differences between the bread samples
350 baked with the various yeast strains. Further observations showed that all bread samples increased in
351 hardness. Measurements conducted after 2h of baking showed that breads baked with S-23, WB-06 and
352 T-58 had a significant softer breadcrumb texture in comparison to Baker's yeast. T-58 however showed
353 the significant lowest hardness in comparison to all applied yeast strains. Bread baked with the yeast
354 strain US-05 showed the significant highest hardness. Similar observations were made by Heitmann et
355 al. [4], who also showed that wheat breads formulated with the yeast strain US-05 had the highest
356 hardness after baking. A similar order of hardness of the different breads baked with the various yeast
357 strains was observed after 24h. Breads baked with US-05 resulted in the significant highest hardness.
358 The applied yeast S-23 and T-58 showed the significant lowest hardness in comparison to the other
359 yeasts, with T-58 having still the significant softest breadcrumb. The application of WB-06 resulted in
360 breads which showed now similar results to the control Baker's yeast, indicating a faster staling process.
361 The differences of the various breads in crumb hardness are hypothesised to be caused by the crumb
362 structure. The hardness of breadcrumb is measured by compression over a certain area (probe diameter
363 20mm). Due to the significant difference in cell diameter, different areas of cell walls are compressed.
364 Hence, it is suggested that breads with high cell diameter provide less cell walls for the measuring probe
365 to compress resulting in less resistance and a lower measurement of hardness. Correlations between
366 dough properties and the final bread properties were found ($r > 0.8$). The dough rise had strong
367 correlations between the crumb cell structure, in particular with the cell diameter ($r. 0.937, p. < 0.001$).
368 This was explained by the production of CO_2 , which expands the crumb cells and in turn increases the
369 dough rise. Based on this, it can be expected to find correlations between the dough rise properties of
370 the doughs and the specific volume of the various breads ($r. 0.844, p. < 0.001$). The found correlation
371 suggests that the dough rise measurement offers the potential to be used as prediction tool for the final
372 volume of baked breads and yeast activity. Correlation analysis also confirmed the discussed connection
373 between cell structure and texture. After baking a higher number of cells was positively correlated with
374 the hardness of the breadcrumb 2 h ($r. 0.870, p. < 0.001$) and 24 hr ($r. 0.929, p. < 0.001$). This suggests
375 that the increase in cells increased the number of cell walls which in turn strengthen the breadcrumb
376 and results in higher hardness values. A further correlation was found for the specific volume and the
377 bake loss ($r. 0.802, p. < 0.001$). This correlation has also been found in a previous study [14] and is
378 known to be caused by a greater specific volume which offers a greater surface area for water to
379 evaporate.

380 **3.7 Volatile Aroma Compounds Analysis**

381 The identification of the aroma compounds revealed ethanol and acetic acid as the only components
382 being detected in all the breadcrumb samples (Table 4). Ethanol, which is the most produced volatile
383 compound during bread fermentation, was also found in this study to be the main compound. The *S.*
384 *cerevisiae* yeast strain T-58 was found to have produced almost twice as much ethanol in comparison
385 to the other yeast strains. The high activity of T-58 was also earlier discussed during the dough-rise

386 measurement and the lower pH in the final bread. Overall it is suggested that it is due to its tolerance to
387 high temperature [4]. Further detected aroma compounds in some of the bread samples were 2,3-
388 butanediol and 1-hydroxy-2-propanone. 2,3- butanediol is a metabolite of alcoholic fermentation, which
389 was found in breads fermented with the yeast strains S-23 and T-58. The metabolic pathway for the
390 production of 2,3- butanediol by yeast was reported to be the oxidative decarboxylation and
391 enzymatically reduction of 2-acetolactat [30]. The production of 2,3-butandiol is discussed to increase
392 ethanol production [31]. However, in this study this effect could not be confirmed. The aroma
393 compound 1-hydroxy-2-propanone was found in breads baked with S-23. This compound is a product
394 of Maillard reaction and created by the reaction between reducing sugars and amino acids, mainly
395 proline [32]. The presence was explained by the pea protein present in the used gluten-free system. A
396 study by Heitmann et al. [4], who applied the same yeasts and conducted the same method for aroma
397 compound determination in a wheat bread found further compounds such as isobutyric acid, 1-hexanol,
398 2-phenylethanol and 3-methyl-1-butanol. The lower diversity of aroma compounds found in the current
399 study is suggested to be caused by the metabolic pathways of the various yeasts, which followed the
400 alcoholic fermentation, rather than the TCA cycle. To produce significant amounts of aroma
401 compounds, conditions like amino acid composition, glucose supply and oxygen must be provided [33].
402 The refined system in this study based on pure potato starch, lacks on nutrients for the yeast growth and
403 the connected metabolite production. Due to the lack of alpha-amylase activity of potato starch [34], no
404 glucose can be generated by degrading the starch. A low content of damaged starch, due to the
405 extraction process of potato starch further prevents the generation of glucose [35].
406 Only the addition of sucrose in the recipe provides a limited amount of glucose after degradation, as
407 seen in Table 2. Hence the main reason for the switch to alcoholic fermentation is assumed to be caused
408 by the liquid batter, which causes depletion of oxygen. Based on these conditions it is hypothesised,
409 that the yeast during fermentation switched to the alcoholic fermentation, rather than following
410 respiration.

411 **3.8 Descriptive sensory evaluation**

412 For the descriptive analysis of the breadcrumb samples, a total of 12 attributes split into aroma and
413 flavour were chosen. The descriptors are listed in Online resource 1. The sensory evaluation of the
414 aroma did not show significant differences between the baked breads with the various yeast strains (data
415 not shown). The outcome of this analysis is explained by the low production of volatile compounds and
416 acids. The used gluten-free system lacks sufficient and or specific nutrients for the yeast to metabolise
417 and produce other products than ethanol and acetic acid. The lack of nutrients for the yeast in a gluten-
418 free system can be confirmed by the volatiles found in wheat-based system, applying the same yeast
419 strains [31]. In a wheat system higher amounts of volatile aroma compounds were found and hence
420 differences in sensory profiles were reported. The outcome of the sensory evaluation suggests that the
421 yeasts can be interchangeably be used without affecting the flavour and aroma profile. This allows
422 focussing on the techno-functional effects of the yeast strains on the dough and final bead.
423

424

4. Conclusion

425 This study was conducted to investigate the effect of different *S. cerevisiae* yeast strains on a gluten-
426 free bread formulation. Although only strains of *S. cerevisiae* were applied, differences in dough and
427 bread quality parameters were observed. Differences in sugar metabolism and preferred fermentation
428 temperatures lead to diverse activity levels and performance of the various yeasts. These differences in
429 activity had major changes in the dough performance and ultimately in the bread baking characteristics.
430 The application of the yeast strain US-05 showed a decrease in loaf volume and a high increase in
431 crumb hardness in comparison to the control yeast. On the contrary T-58 resulted in the bread with the
432 highest loaf volume and the softest bread crumb. The yeast strain WB-06 showed the closest
433 resemblance to the breads baked with the control yeast strain Baker's yeast. Pearson analysis showed
434 significant correlations between yeast activity indicators such as pH and remaining levels of sugar and
435 the dough rise parameters ($r. > 0.70$) (Online resource 2). These in turn correlated with loaf volume
436 crumb structure and texture of the baked breads ($r. > 0.75$). Volatile aroma compound analysis detected
437 only low amounts of volatiles which explained the not significant different results of the descriptive
438 sensory. The low production of volatiles was explained to be caused by the refined gluten-free system
439 in this study, which lacks nutrients for the yeast metabolism. In summary it was found that the different
440 yeasts only affected the technological properties rather than the flavour and aroma profile of the baked
441 breads. This was found to be due to the yeast specific activities and properties. The performed study
442 demonstrated the suitability of different yeast strains of *S. cerevisiae* in the application of gluten-free
443 bread.

444 **Conflict of interest:**

445 The authors declare that they have no competing interest

446

447 **Compliance with ethics requirements:**

448 This article does not contain any studies with human or animal subjects.

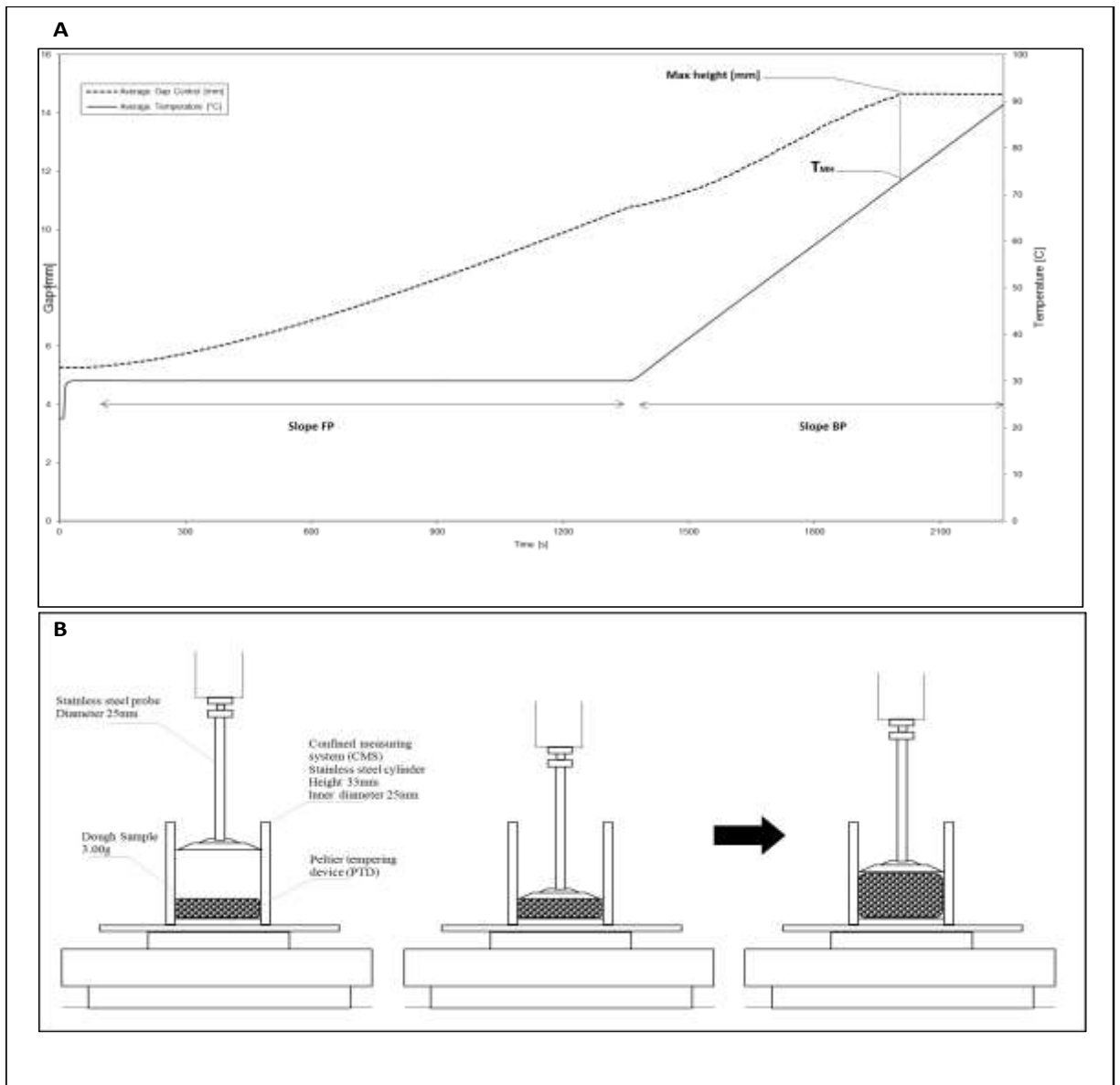
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450 **References**

- 451 1. Linko, Y.-Y., P. Javanainen, and S. Linko, *Biotechnology of bread baking*.
452 Trends in food science & technology, 1997. **8**(10): p. 339-344.
- 453 2. Fleet, G.H., *Yeasts in foods and beverages: impact on product quality and*
454 *safety*. Current opinion in biotechnology, 2007. **18**(2): p. 170-175.
- 455 3. Rezaei, M.N., et al., *Harvesting yeast (Saccharomyces cerevisiae) at different*
456 *physiological phases significantly affects its functionality in bread dough*
457 *fermentation*. Food microbiology, 2014. **39**: p. 108-115.
- 458 4. Heitmann, M., E. Zannini, and E.K. Arendt, *Impact of different beer yeasts*
459 *on wheat dough and bread quality parameters*. Journal of Cereal Science,
460 2015. **63**: p. 49-56.
- 461 5. Amendola, J. and N. Rees, *Understanding the Art and Science of Baking*.
462 2003, John Wiley and Sons: Hoboken, NJ.
- 463 6. Heitmann, M., E. Zannini, and E. Arendt, *Impact of Saccharomyces*
464 *cerevisiae metabolites produced during fermentation on bread quality*
465 *parameters: A review*. Critical reviews in food science and nutrition, 2017: p.
466 1-13.
- 467 7. Koehler, P., H. Wieser, and K. Konitzer, *Celiac disease and gluten:*
468 *multidisciplinary challenges and opportunities*. 2014: Academic Press.
- 469 8. Tsatsaragkou, K., et al., *Improving carob flour performance for making*
470 *gluten-free breads by particle size fractionation and jet milling*. Food and
471 Bioprocess Technology, 2017. **10**(5): p. 831-841.
- 472 9. Lai, H. and T. Lin, *Bakery products: science and technology*. Bakery
473 products: Science and technology, 2006: p. 3-65.
- 474 10. Birch, A.N., et al., *Influence of commercial baker's yeasts on bread aroma*
475 *profiles*. Food Research International, 2013. **52**(1): p. 160-166.
- 476 11. Birch, A.N., M.A. Petersen, and Å.S. Hansen, *Aroma of wheat bread crumb*.
477 Cereal Chemistry, 2014. **91**(2): p. 105-114.
- 478 12. Pico, J., J. Bernal, and M. Gómez, *Wheat bread aroma compounds in crumb*
479 *and crust: A review*. Food Research International, 2015. **75**: p. 200-215.
- 480 13. Randez-Gil, F., P. Sanz, and J.A. Prieto, *Engineering baker's yeast: room for*
481 *improvement*. Trends in biotechnology, 1999. **17**(6): p. 237-244.
- 482 14. Horstmann, S., M. Foschia, and E. Arendt, *Correlation analysis of protein*
483 *quality characteristics with gluten-free bread properties*. Food & function,
484 2017. **8**(7): p. 2465-2474.
- 485 15. Penninckx, M.J., *An overview on glutathione in Saccharomyces versus non-*
486 *conventional yeasts*. FEMS yeast research, 2002. **2**(3): p. 295-305.
- 487 16. Verheyen, C., et al., *The contribution of glutathione to the destabilizing effect*
488 *of yeast on wheat dough*. Food chemistry, 2015. **173**: p. 243-249.
- 489 17. Reed, G., *Yeast technology*. 2012: Springer Science & Business Media.

- 490 18. Delcour, J. and R.C. Hoseneey, *Principles of cereal science and technology*
 491 *authors provide insight into the current state of cereal processing*. Cereal
 492 Foods World, 2010. **55**(1): p. 21-22.
- 493 19. Yano, H., *Improvements in the bread-making quality of gluten-free rice*
 494 *batter by glutathione*. Journal of agricultural and food chemistry, 2010.
 495 **58**(13): p. 7949-7954.
- 496 20. White, C. and J. Zainasheff, *Yeast: the practical guide to beer fermentation*.
 497 2010: Brewers Publications.
- 498 21. Struyf, N., et al., *Bread Dough and Baker's Yeast: An Uplifting Synergy*.
 499 *Comprehensive Reviews in Food Science and Food Safety*, 2017. **16**(5): p.
 500 850-867.
- 501 22. Frasse, P., et al., *The influence of fermentation on volatile compounds in*
 502 *French bread dough*. LWT-Food Science and Technology, 1993. **26**(2): p.
 503 126-132.
- 504 23. Verheyen, C., M. Jekle, and T. Becker, *Effects of Saccharomyces cerevisiae*
 505 *on the structural kinetics of wheat dough during fermentation*. LWT-Food
 506 Science and Technology, 2014. **58**(1): p. 194-202.
- 507 24. Sluimer, P., *Principles of breadmaking: functionality of raw materials and*
 508 *process steps*. 2005.
- 509 25. Cauvain, S.P. and L.S. Young, *Technology of breadmaking*. 2016: Springer.
- 510 26.
- 511 27. Hager, A.-S., et al., *Investigation of product quality, sensory profile and*
 512 *ultrastructure of breads made from a range of commercial gluten-free flours*
 513 *compared to their wheat counterparts*. European Food Research and
 514 Technology, 2012. **235**(2): p. 333-344.
- 515 28. Morreale, F., R. Garzón, and C.M. Rosell, *Understanding the role of*
 516 *hydrocolloids viscosity and hydration in developing gluten-free bread. A*
 517 *study with hydroxypropylmethylcellulose*. Food Hydrocolloids, 2017.
- 518 29. Gray, J. and J. Bemiller, *Bread staling: molecular basis and control*.
 519 *Comprehensive reviews in food science and food safety*, 2003. **2**(1): p. 1-21.
- 520 30. Wainwright, T., *Diacetyl—A review: Part I—Analytical and biochemical*
 521 *considerations: Part II—Brewing experience*. Journal of the Institute of
 522 Brewing, 1973. **79**(6): p. 451-470.
- 523 31. Heitmann, M., et al., *Correlation of Flavor Profile to Sensory Analysis of*
 524 *Bread Produced with Different Saccharomyces cerevisiae Originating from*
 525 *the Baking and Beverage Industry*. Cereal Chemistry, 2017. **94**(4): p. 746-
 526 751.
- 527 32. Tressl, R., et al., *Formation of proline-and hydroxyproline-specific Maillard*
 528 *products from [1-13C] glucose*. Journal of agricultural and food chemistry,
 529 1993. **41**(4): p. 547-553.
- 530 33. Otterstedt, K., et al., *Switching the mode of metabolism in the yeast*
 531 *Saccharomyces cerevisiae*. EMBO reports, 2004. **5**(5): p. 532-537.

- 532 34. Horstmann, S.W., et al., *Fundamental study on the impact of gluten-free*
533 *starches on the quality of gluten-free model breads*. Foods, 2016. **5**(2): p. 30.
- 534 35. Horstmann, S.W., K.M. Lynch, and E.K. Arendt, *Starch characteristics*
535 *linked to gluten-free products*. Foods, 2017. **6**(4): p. 29.
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Figure 1 A: Example diagram for Time- and temperature-dependent rising behaviour of dough. B: Flow chart of methodology

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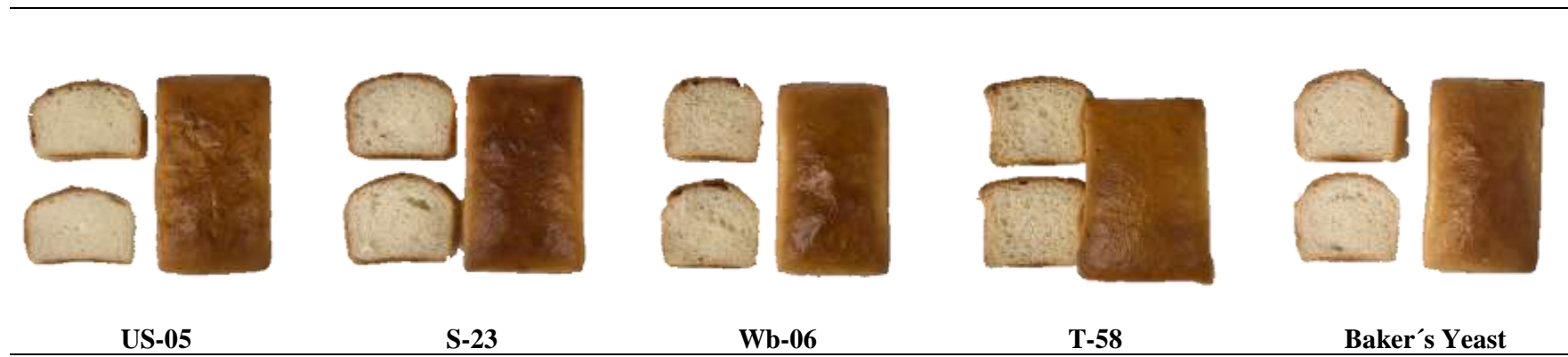


Figure 2 Images of cross section and surface of breads baked with the various yeast strains

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545 Table 1 Properties of the different yeast strains

<i>S. cerevisiae</i>	Application ¹	Temperature optimum [C] ¹	Fermentation time ¹	Activity [cfu/g] ²	Dosage [%] ²	Sugar metabolism ¹			
						MalT	Mal	Glu	Dextr
Baker's yeast	Baked goods	25-30	Hours	1.06 E+09	2	++	+	+	+
S-23	Lager	12-15 (27 faster) lower temperature tolerance	Up to 14 days	5.18 E+08	4.1	++	+++	+++	+
T-58	Ale	15-20 (32 faster) High temperature tolerance	2-3 days	5.5 E+08	3.86	++	++	++	+++
US-05	Ale	15-22 high temperature tolerance	2-3 days	4.47 E+08	4.48	+++	+	+++	++
WB-06	Wheat Beer	18-24	2-3 days	7.16 E+08	2.97	+	++	++	++

546 ¹Adapted from Heitmann et al., (Heitmann, Axel, Zannini, & Arendt, 2017) with modifications

547 ²From yeast activity measurement

548 MalT: Maltotriose; Mal: Maltose; Glu: Glucose; Dextr: Dextrins

549 +++ high; ++ moderate; + low

550

551

552 Table 2 Chemical and functional properties of the bread doughs containing the different yeast strains

		US-05	WB-06	T-58	S-23	Baker's Yeast
Total starch (dm)	Dough [g/100g]	84.78 +/- 5.38 ^a	81.54 +/- 4.69 ^a	82.71 +/- 5.63 ^a	84.13 +/- 8.66 ^a	78.00 +/- 1.68 ^a
	Bread [g/100g]	82.09 +/- 4.24 ^{ab}	81.50 +/- 4.14 ^{ab}	75.97 +/- 1.67 ^b	78.57 +/- 2.24 ^b	87.27 +/- 0.87 ^a
Sugars	Glucose					
	Dough [g/100g]	2.30 +/- 0.60 ^a	2.70 +/- 0.18 ^a	1.94 +/- 0.54 ^a	2.30 +/- 0.04 ^a	1.85 +/- 0.14 ^a
	Bread [g/100g]	2.23 +/- 0.45 ^a	1.24 +/- 0.05 ^b	0.37 +/- 0.07 ^c	1.21 +/- 0.09 ^b	1.17 +/- 0.02 ^b
	Fructose					
	Dough [g/100g]	2.03 +/- 0.24 ^a	2.25 +/- 0.12 ^a	2.02 +/- 0.03 ^a	2.02 +/- 0.03 ^a	2.24 +/- 0.10 ^a
	Bread [g/100g]	2.30 +/- 0.41 ^a	1.54 +/- 0.54 ^{ab}	1.12 +/- 0.05 ^b	1.55 +/- 0.09 ^{ab}	1.61 +/- 0.03 ^{ab}
pH	Dough [-]	5.12 +/- 0.04 ^a	4.96 +/- 0.01 ^b	4.77 +/- 0.04 ^c	5.14 +/- 0.01 ^a	4.98 +/- 0.03 ^b
	Proofed Dough [-]	4.88 +/- 0.04 ^a	4.84 +/- 0.01 ^{ab}	4.54 +/- 0.01 ^c	4.85 +/- 0.10 ^{ab}	4.72 +/- 0.00 ^b
	Bread [-]	5.26 +/- 0.02 ^{ab}	5.29 +/- 0.02 ^a	5.05 +/- 0.03 ^c	5.20 +/- 0.03 ^b	5.20 +/- 0.04 ^b
Dough Rise	SlopeFP [mm/min]	0.04	0.09	0.27	0.10	0.13
	SlopeBP [mm/min]	0.30	0.53	0.43	0.53	0.39
	MaxH [mm]	10.09 ± 0.04 ^d	16.01 ± 0.59 ^b	21.78 ± 0.29 ^a	17.13 ± 0.21 ^b	14.65 ± 0.93 ^c
	T _{MH} [°C]	82.01 ± 0.02 ^c	89.92 ± 0.01 ^a	83.10 ± 0.04 ^b	89.91 ± 0.01 ^a	74.96 ± 0.03 ^d

553 Means in the same row with different letters are significantly different (≥ 3 = One-way ANOVA; ≥ 2 = t-Test, $p < 0.05$). n.d. = not detected

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558 Table 3 Results of bread parameters baked with the different yeast strains

559

Yeast strain	US-05	S-23	WB-06	T-58	Baker's Yeast
Specific Volume [ml/g]	1.96 ± 0.05 ^d	2.18 ± 0.12 ^c	2.50 ± 0.08 ^b	3.43 ± 0.28 ^a	2.42 ± 0.11 ^b
Bake Loss [g/100g]	15.36 ± 0.25 ^c	16.61 ± 0.28 ^b	17.34 ± 0.79 ^b	19.36 ± 1.18 ^a	16.88 ± 0.38 ^b
Number of Cells [-]	3192.1 ± 205.2 ^a	2517.056 ± 71.7 ^c	2430.889 ± 195.0 ^c	2297.529 ± 226.6 ^d	2534.278 ± 124.7 ^b
Cell Diameter [mm]	1.43 ± 0.10 ^d	2.00 ± 0.21 ^c	2.43 ± 0.23 ^b	3.69 ± 0.22 ^a	2.54 ± 0.22 ^b
Number of Cells/ Slice Area (mm²)	0.805 ± 0.063 ^d	0.560 ± 0.049 ^c	0.490 ± 0.039 ^b	0.377 ± 0.026 ^a	0.508 ± 0.031 ^b
Hardness (2h) [N]	8.26 ± 1.26 ^a	4.10 ± 1.18 ^c	3.86 ± 0.50 ^c	2.19 ± 0.46 ^d	5.82 ± 0.92 ^b
Hardness (24h) [N]	29.91 ± 3.64 ^a	14.62 ± 1.82 ^c	16.67 ± 1.82 ^b	6.33 ± 1.17 ^d	16.75 ± 2.00 ^b

Means in the same row with different letters are significantly different (≥ 3 = One-way ANOVA; ≥ 2 = t-Test, $p < 0.05$).
n.d. = not detected

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562 Table 4 Volatile compound analysis

Compound	Organoleptic description ¹	Concentration [$\mu\text{g}/\text{kg}$]				Baker's Yeast
		S-23	T-58	US-05	WB-06	
Ethanol	Alcoholic, sweet	2500	5800	2300	2300	3000
Acetic Acid	Vinegar, pungent, sour	1300	360	120	200	260
2,3-Butandiol	Fruity, creamy, buttery	300	160	n.d.	n.d.	n.d.
1-Hydroxy-2-propanone	Pungent, sweet, caramellic, ethereal	190	n.d.	n.d.	n.d.	n.d.

563 ¹Described according to (Pico et al., 2015)

564 n.d.= not detected

565

566 **Online resources**

567 Online resource 1 Sensory descriptors

Smell (Odour)	Description
Whey	Aroma typical of Whey powder
Eggy	Aromatic characteristics of boiled eggs (sulphuric)
Nutty	Aromatic characteristics of mixed nuts, e.g. walnuts, hazelnuts, brazil nuts and pine nuts
Green (pungent)	Aroma typical of cut grass
Cereal (bread)	Aroma typical of cereals (oats, rye, barley, wheat) mixed with boiling water 1:3
Intensity	Perceived first impression of odour intensity of breadcrumb
Taste (Flavour)	
Salty	Degree of perceived salty taste, as a basic taste
Acidic / Sour	Degree of sourness taste
Yeasty	Flavour associated with natural yeast as a leavening agent
Green (pungent)	Itchy trigeminal sensation on the tip of the tongue
Aftertaste	Flavour of crumb staying after tasting
Intensity	Intensity of overall flavour in crumb

568

569 Online resource 2 Correlation of dough properties with final bread characteristics

570 Pearson correlation: *p. < 0.5, ** p. < 0.1, *** p.< 0.01

571

Dough Rise properties			
		Max Height [mm]	Slope 30C
pH proofed Bread		-0.728**	-0.921***
Yeast activity	pH Bread	-0.744**	-0.911***
	Glucose Bread	-0.922***	-0.879***
	Fructose Bread	-0.793***	-0.723**
	Cell Diameter	0.849***	0.937***
Bread properties	Number of Cells /	-0.885***	-0.789***
	Slice Area (mm)	0.844***	0.937***
	Specific Volume	0.844***	0.937***
	Hardness 0h	-0.910***	-0.730**
	Hardness 24h	-0.948***	-0.851***

572