1	An Ohmic heating study of the functionality						
2	of leavening acids in cream cake systems						
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20 *O. Abstract*

21 Temperature gradients during cake baking complicate the study of leavening agent functionality, as 22 leavening acid solubility and dissolution rate determine the moment of carbon dioxide (CO₂) 23 production. To control batter temperature, cream cake batter was baked in an electrical resistance oven 24 (ERO). Simultaneously, CO₂ release in the ERO headspace and cake height were monitored. Furthermore, 25 CO₂ production and release were linked to thermal transitions in the cake batter (DSC) and crumb structure setting (RVA). Early-acting organic acids produced high amounts of CO₂ during mixing which 26 27 could not be retained. This yielded low volume cakes. Sodium acid pyrophosphate and late-acting organic 28 acids resulted in high quality cakes. However, CO₂ production after crumb setting did not (further) 29 improve cake quality, which implies suboptimal use of leavening power. This study highlights the 30 importance of CO_2 production during the early baking phase and illustrates the value of the ERO set-up 31 for studying leavening agents.

32 1. Introduction

Worldwide consumption of bakery products increases by *ca*. 2.6% every year (Mordor Intelligence, 2021).
A considerable share of such products are leavened. Cream cake is typically leavened by chemical
leavening agents. Besides leavening agents, typical cream cake ingredients are flour, sugar, eggs, and oil
(Godefroidt, Ooms, Pareyt, Brijs & Delcour, 2019).

Chemical leavening agents produce carbon dioxide (CO₂) during dough/batter preparation and baking. They generally consist of a leavening salt and a leavening acid (Heidolph, 1996; LaJoie & Thomas, 1994). The most common leavening salt is sodium bicarbonate (NaHCO₃) (LaJoie & Thomas, 1994). It produces CO₂ either by reacting with an acid (reaction 1), or through a thermally driven decomposition reaction in the (late) baking phase in which it is converted into sodium carbonate, water, and CO₂ (reaction 2). In the thermal decomposition reaction, only 50% of the theoretical amount of CO₂ produced in reaction 1 is formed (Hartman, Svoboda, Pohořelý & Šyc, 2013).

44
$$NaHCO_3 + HX \rightarrow NaX + H_2O + CO_2$$
 (1)

45
$$2 \operatorname{NaHCO}_3 \rightarrow \operatorname{Na_2CO}_3 + H_2O + CO_2$$
 (2)

As the time of CO₂ production due to thermal decomposition is hard to control since NaHCO₃ only
decomposes into CO₂ at high temperatures (Keener, Frazier & Davis, 1985), thermal decomposition is not
preferred in most cake systems.

The most important cake leavening acids are summarized elsewhere (Godefroidt et al., 2019; Russell, 2018) and are mainly selected based on the moment of CO₂ production (Russell, 2018). Since NaHCO₃ immediately dissolves during mixing, CO₂ production during cake making depends on the solubility and dissolution rate of the leavening acid, and the rate of reaction (1) in the aqueous phase of the batter (Heidolph, 1996; Miller, 2015). As baking progresses, the rate of dissolution, the solubility, and the rate of reaction (1) increase and result in increased CO₂ production. Some leavening acids dissolve and react mostly during mixing. These are the so-called fast-acting leavening acids. When slow(er)-acting acids are used, CO₂ is produced later, *i.e.* mostly at higher temperatures during baking. However, CO₂ production should not occur after the cake structure has set as it then causes cracks in the crumb due to the increased internal pressure (Heidolph, 1996; Miller, 2015).

An important characteristic of a leavening acid is its neutralizing value (NV), *i.e.* the amount of NaHCO₃
necessary to neutralize 100 parts of the acid by weight (Holmes & Hoseney, 1987; Russell, 2018). It is used
to calculate the dosage of the leavening acid.

Most commercial cake leavening acids are inorganic phosphates. They are chosen due to the ease with which CO₂ production can be controlled, and because of their favorable price (Russell, 2018). A prominent example is sodium acid pyrophosphates (SAPPs). By adapting their manufacturing, the amount of CO₂ produced during mixing can be controlled (Russell, 2018). SAPPs are generally typified with a number which provides an estimate of the CO₂ production during mixing, expressed as a percentage of the maximum CO₂ production capacity when NaHCO₃ is dosed according to the SAPP's NV. SAPP₂₈ qualifies as a 'slow-acting' leavening acid (Miller, 2015).

We here studied how the timing of CO_2 production impacts cream cake quality. In particular, we compared the functionality of the leavening acid SAPP₂₈ (NV = 72, solubility in water 119 g/L at 20 °C) with that of food-grade organic acids of varying solubility, *i.e.* fumaric acid (NV = 145, 7 g/L at 25 °C), adipic acid (NV = 115, 30 g/L at 30 °C), α -ketoglutaric acid (NV = 115, 100 g/L at 25 °C), and citric acid (NV = 159, 592 g/L at 25 °C) (PubChem, 2020). A sample containing only NaHCO₃ was also tested.

To assess the functionality of these acids during baking, an electrical resistance oven (ERO) rather than a conventional oven was used. During conventional cake baking the temperature increases at different rates in different locations in the batter (Deleu *et al.*, 2019). This complicates the study of temperatureinduced phenomena. In contrast, Ohmic heating (also called electrical resistance heating) results in an
essentially uniform rise of the temperature and, thus, without major temperature gradients (Masure,
Wouters, Fierens & Delcour, 2019; Deleu *et al.*, 2019).

When performed in a sealed ERO, the setup allows to monitor CO₂ release in the headspace when coupled
to a CO₂ analyzer. As it allows simultaneous monitoring of batter temperature, batter height, and CO₂
release, this set-up is particularly interesting for studying leavening acid functionality during cake baking.
The effect of the different acids on batter density, and volume and texture of conventionally baked cream
cakes was examined.

85 2. Materials and methods

86 2.1. Materials

Commercial wheat flour [moisture content, 14.0%; protein content, 11.6% (dry basis, N x 5.7)], NaHCO₃,
SAPP₂₈, and monoacylglycerol and diacylglycerol based emulsifier were provided by Puratos (GrootBijgaarden, Belgium). Solvents, chemicals, and reagents were from Sigma-Aldrich (Bornem, Belgium) and
of at least analytical grade. Ultra-fine sugar, rapeseed oil, and hen eggs were obtained from a local
supermarket.

92 2.2. Cake batter making

93 Cream cake ingredients and their relative levels in the batter are listed in Table 1. Egg white and yolk of 94 fresh eggs were first separated so that the levels added could accurately be controlled. The leavening acid 95 amounts were based on their NV, *i.e.* 72, 145, 114, 114, and 159 for SAPP₂₈, fumaric, adipic, α-ketoglutaric, 96 and citric acid respectively. Cream cake batters (1,875 g) were prepared in triplicate by single-stage 97 mixing. Wheat flour, sucrose, NaHCO₃, leavening acid, and emulsifier were first blended together. 98 Afterwards, water, rapeseed oil, egg white, and egg yolk were manually folded into the blend of the dry components with a spatula. The batter was then mixed with a Hobart N-50 5-Quart Mixer (Troy, OH, USA)
for 2 min at speed 1. After manually scraping the batter from the edges of the bowl with a spatula, it was
mixed for an additional 2 min at speed 2 with the same mixer.

102 2.3. Batter density determination

The weight of 100 ml of each individual batter was determined in duplicate with a tared plastic cylinder
and used to calculate its density (Wilderjans, Pareyt, Goesaert, Brijs & Delcour, 2008).

105 2.4. Differential scanning calorimetry

Samples of each individual batter were analyzed with a DSC Q2000 (TA Instruments, New Castle, DE, USA) to determine the temperature range over which starch gelatinization and protein denaturation occurred. Batter samples (8.0 mg) were accurately weighted in coated aluminum pans (Perkin Elmer, Waltham, MA, USA). The pans were hermetically sealed, equilibrated at 22 °C, and then heated until 120 °C at 7.4 °C/min. Measurements were done together with an empty reference pan. The temperatures characterizing the endothermic transitions(s) [onset (T_0) and peak temperature (T_p)] and enthalpy (Δ H) values were calculated with TA Universal Analysis software.

113 2.5. Rapid viscosity analysis (RVA)

Viscosity development of each individual batter during heating was analyzed with an RVA Super 4 (Perten, Hägersten, Sweden). An RVA cup was filled with batter (25 g) until the spindle was fully submerged. The batter was then submitted to the temperature-time profile measured in the center of a conventionally baked cream cake (*cfr.* 2.7.1.). Batter viscosity was calculated from the current required to mix the batter during heating with a rotating paddle at a constant speed of 75 rpm and was measured every 8 seconds. The temperature at which structure setting started to occur, which is here defined as the temperature after which viscosity had increased by >10% over the span of three consecutive measurements, was also
determined. All measurements were done in duplicate.

122 2.6. Cake baking

2.6.1. Electrical resistance oven baking and carbon dioxide measurement

124 A quantity (400 g) of each individual cream cake batter was brought into an acrylic glass ERO (length x 125 width x height, 150 x 95 x 180 mm) between two stainless steel electrode plates (60 mm apart). The ERO 126 was then sealed with an acrylic glass lid. A proportional-integral-derivative (PID) feedback controller (Jumo 127 Automation, Eupen, Belgium) was used to adjust the voltage to bring about the desired temperature-time 128 profile, *i.e.* 23 min at a heating rate of 3 °C/min (from 21 °C to 90 °C), followed by 8 min at a heating rate 129 of 1.25 °C/min (from 90 °C to 100 °C), followed by an isothermal step at 100 °C for 9 min. This profile was 130 based on that in the center of a cream cake baked in a conventional plate oven (cfr. 2.6.2.), as registered with a type T thermocouple (DataPaq, Cambridge, UK). The same thermocouple was used to monitor the 131 132 batter temperature during Ohmic heating. Batter height was read every min on a ruler attached to the 133 side of the ERO. A 100% CO₂ Sampling Data Logger (CO2Meter, Ormond Beach, FL, USA) was connected 134 to the headspace of the ERO with filter tubes containing a hydrophobic filter, a particle filter, and a water 135 trap (CO2Meter). Its input was applied to the side of the ERO, while its output was applied to the top 136 (Figure 1). In doing so, the CO_2 data logger thus measured the accumulated CO_2 level present in the 137 headspace of the ERO. Prior to every measurement, the data logger was calibrated to the actual amount of CO_2 in the headspace of the ERO; 410 ppm / 0.041% CO_2 (amount of CO_2 in the atmosphere). 138

139 2.6.2. Conventional baking

Of each individual batter, 220 g was added to each of five aluminum baking tins (length x width x height,
170 x 75 x 50 mm) (Gents Bakkershuis, Ghent, Belgium). The cakes were baked in a plate oven (Hein

142 Condilux, Hein, Strassen, Luxembourg) at 180 °C for 40 min. After cooling for 120 min at 23 °C, the cakes
143 were weighed and their volume was determined with a VolScan Profiler (Stable Micro Systems,
144 Godalming, UK). Weight and volume were then used to calculate cake density.

145 2.7. Texture analysis

146 Texture profile analysis (TPA) was performed essentially as in Luyts et al. (2013) and Wilderjans et al. 147 (2008). Crumb texture was determined with an Instron (Norwood, MA, USA) 3342 texture analyzer 148 equipped with a cylindrical probe (diameter of 75 mm) and a 50 N load cell. Measurements were 149 performed on the five cakes made from each individual cake batter (cfr. 2.6.2.). Of each cake, four 25 mm 150 thick crumb slices were cut. A 30 mm diameter cylindrical crumb sample was cut from each of these slices 151 with a stainless-steel cutting tool. The cylindrical probe compressed the cake crumb samples to 50% of 152 their original height at 2 mm/s, after which the sample was decompressed. The compression-153 decompression cycle was then repeated after a resting period of three s. In what follows, crumb 154 springiness is the time it took for the probe to deform the sample during the second deformation divided 155 by the time it took to deform the sample during the first deformation. Crumb cohesiveness is the ratio of 156 the total force needed to compress the sample a second time to the force needed to compress it the first time. Its resilience is the ratio of the force the sample exerted on the probe during the upward movement 157 158 of the probe to the force the probe itself exerted on the sample during the downward movement. 159 Springiness indicates how well crumb returns to its original height after a first deformation, resilience how 160 well the sample withstands the (first) deformation, and cohesiveness how well it withstands a second 161 deformation. Finally, crumb firmness is the pressure needed to compress the sample to 50% of its original 162 height during the first compression cycle. The 'corrected firmness' is the firmness divided by the cake density and expressed in N*cm³/g (Bosmans, Lagrain, Fierens & Delcour, 2013). 163

164 2.8. pH measurements

Batter pH was determined with an HI-9126 pH meter (Hanna Instruments, Woonsocket, RI, USA). To provide an estimate of the pH of the aqueous phase of cake samples, a saturated solution of phenol red in deionized water was administered to a cake slice crumb. This pH indicator exhibits a gradual transition from yellow to red over the pH range 6.8 to 8.2. Above pH 8.2, it turns into a bright pink color. In cake systems, there is an additional yellow/brown background due to the base color of the cake. The color pHscale is shown on the right side of Figure 4.2.

171 2.9. Statistical analysis

Analysis of variance (ANOVA) was used to compare averages of batter density and pH, CO₂ accumulation
values, and cake volume, height and texture properties. The Tukey method (P < 0.05) was applied to detect
differences in said parameters using JMP Pro 11 (SAS Institute, Cary, NC, USA).

175 *3. Results and discussion*

176 3.1. Batter properties

177 The effects of different leavening acids on batter density and pH are summarized in Table 2. No differences 178 in batter density were detected. While one may argue that this was due to the produced CO_2 being 179 dissolved in the aqueous phase of the batter (Teng & Yamasaki, 1998), even with slow acting baking acids 180 the aqueous batter phase would quickly become saturated with CO₂. Indeed, when taking into account 181 the partial pressure of CO_2 (4.0 10^{-4} atm) in air (the main components of which are N₂ and O₂), CO_2 solubility in water is 1.36 10^{-5} mol_{co2}/L_{H2O}. Since the aqueous phase of batter can be considered to be a 182 183 sucrose syrup, CO₂ solubility in batter is even lower, as it is negatively impacted by increasing levels of 184 sucrose (Vázquez et al., 1994). At the level of NaHCO₃ used here (1.1 g_{NaHCO3}/197.1 g_{solvent}), and assuming 185 a solvent density of 1.2 g/L for a sucrose solution of 45% (89 gsucrose/197.1 gsolvent; Table 1) (Engineering 186 Toolbox, 2020), approximately 7.97 10^{-2} mol_{CO2}/L_{solvent} can be produced by the baking powder. Thus, when

a baking acid is used, very little of the CO₂ produced can remain dissolved in the aqueous phase of the
batter.

Based on the reasoning above, the lack of differences in batter density measured for this sample set cannot be due to the CO_2 dissolving in the aqueous phase. We therefore reason that, as a result of the mixing action, part of the CO_2 gas produced is lost from the batter.

- When the batter contained not only NaHCO₃ but also a leavening acid, the leavening system as a whole acted as a buffer. This explains why the batters with different leavening acids had a similar pH (pH = 6.65-7.04). The pH of samples only containing NaHCO₃ was higher (pH = 7.46).
- 195 3.2. Electrical resistance oven baking

The batter/cake crumb temperature, height, and CO_2 release profiles of the SAPP₂₈ containing samples (further referred to as control samples) are shown in Figure 2 along with the RVA data. The baking times associated with the DSC T_o (88.6 ± 0.9 °C) and T_p (96.2 ± 1.1 °C) are indicated as well (*cfr*. Table 2). These transitions involve both starch gelatinization and protein denaturation. Their endotherms cannot be distinguished from one another when analyzing cake batter.

201 During baking of the control samples, four different stages were distinguished. In a first stage (Figure 2.1, 202 up to about 65 °C), neither an increase in height nor CO_2 release were detected. Also, insufficient CO_2 was 203 produced and released to result in noticeable bubble growth (Shah, Campbell, Mckee & Rielly, 1998). 204 Batter viscosity decreased during this early baking stage. The second stage (Figure 2.2, from about 65 to 205 88 °C) was characterized by a steep increase in cake height. The gas cells in the batter expanded 206 significantly due to production of a large amount of CO_2 (Heidolph, 1996). Additionally, CO_2 previously 207 present in the aqueous batter phase became less soluble (Diamond & Akinfiev, 2003). Indeed, the 208 solubility of CO_2 in water at 75 °C is only 45% that at room temperature (Lucile *et al.*, 2012). That no CO_2

209 release from the batter was detected during this phase indicates that the gas cells in the batter remained 210 stable during expansion. At the beginning of the third stage (Figure 2.3, from about 88 to 100 °C), structure 211 setting started, which we here determined as the steep viscosity increase resulting from the transition of 212 a liquid batter to a solid cake matrix, as determined with the RVA. The temperature at which the batter 213 viscosity in the RVA started to increase was highly reproducible (stdev. < 3.5% for all samples), whereas 214 the RVA peak and end viscosity values were not. In the tested batter systems, the dry matter content 215 (70%) by far exceeded that of the diluted flour-water systems typically tested in an RVA set up (9-12% dry 216 matter). Once a solid matrix started forming, the RVA peddle disrupted the batter/cake system 217 completely, which resulted in non-reliable results. Therefore, in what follows, we only focus on the 218 temperature of the start of structure setting. For the control cakes, said temperature was 88.4 (± 0.8) °C. 219 This coincided with the onset temperature of starch gelatinization and protein denaturation as measured 220 with DSC (cfr. Table 2) (Wilderjans, Luyts, Goesaert, Brijs & Delcour, 2010). Furthermore, gas cell opening 221 started occurring around the same time, as indicated by the gradual release of CO₂ from the batter/cake. 222 Cake height still increased slightly in the beginning of this phase, implying that gas expansion and/or 223 production outweighed gas loss due to gas cell opening. At this point during baking, besides CO₂ gas, 224 steam formation may also have aided leavening (Willhoft, 1973). At the end of this phase, the maximum 225 cake height had been reached and the cumulative CO₂ level in the ERO headspace remained constant, 226 indicating that the cake matrix had become fully permeable. During the final baking stage (Figure 2.4, at 227 100 °C) little, if any, additional CO_2 was produced as all of the baking powder had reacted. When 228 interpreting the CO_2 data, one can establish that the CO_2 peak coincides with the start of some limited 229 cake collapse. This a small decrease in cake height is due to the nature of ERO-baking, which results in 230 crustless cakes (Luyts et al., 2013). Indeed, as no crust is formed, ERO cakes are more prone to collapse, 231 both during the final stage of baking and during cooling (Wilderjans, Luyts, Brijs & Delcour, 2013).

Figure 3 shows the height, temperature, and CO₂ release profiles in function of time for all tested leavening acids. As the same amount of NaHCO₃ was added and all leavening agents were dosed based on their NVs, the leavening power was the same for all samples containing leavening acid (Russell, 2018). The differences in reported CO₂ release during baking can therefore be attributed to the amount of CO₂ lost during mixing.

237 Cake recipes containing SAPP₂₈ (i.e. control samples), fumaric acid or adipic acid resulted in similar 238 moments of CO₂ release, which coincided with the temperature of structure setting (Table 2). Fumaric 239 acid use resulted in a CO₂ release profile and cake height profile comparable to that of the control samples. 240 Cakes containing adipic acid however showed higher CO₂ release during baking. Like SAPP₂₈, both fumaric 241 and adipic acid can therefore be categorized as slow-acting leavening acids. Only low amounts of these 242 acids dissolved and/or reacted in the aqueous phase of the batter during mixing, resulting in little CO₂ 243 production and loss during mixing. This resulted in high CO₂ production during baking and significant 244 leavening. While more CO₂ was produced in and released from adipic acid containing batters during baking 245 than in and from control batters, this did not result in a significant increase of cake height during ERO 246 baking. Thus, suboptimal leavening occurred in this case presumably as a result of the very late production 247 of part of the CO_2 . Once the crumb structure has fully set, additionally produced CO_2 freely passes through 248 the cake structure and cannot contribute to further leavening (Miller, 2015). It is clear from Figures 2 and 249 3 that CO₂ release in samples prepared with adipic acid only started to differ from that in the control cakes 250 at the end of baking when the structure had already fully set. These results show the importance of the 251 moment of CO₂ production for optimum cream cake properties.

Figure 3 also shows the height, temperature, and CO_2 release profiles for the samples containing only NaHCO₃. As outlined above, thermal decomposition of NaHCO₃ can maximally supply only half of the amount of CO_2 that is formed when NaHCO₃ reacts with a leavening acid [formulas (1) and (2)] (Hartman *et al.*, 2013). Additionally, NaHCO₃ may not be fully decomposed by the end of baking. This can put further limits on CO₂ production. The limited cake leavening in these samples in the early baking phase is likely mainly due to gas expansion as a result of the increasing temperature and/or steam formation, as no thermal degradation of NaHCO₃ would be expected at this point (Hartman *et al.*, 2013; Russell, 2018). CO₂ release was detected only after 30 minutes of baking, which was significantly later than in the control samples. The reason may be that significant production of CO₂ in the absence of a leavening acid likely only started at this point during baking and/or that any CO₂ production that did occur earlier likely did not result in sufficient pressure build up in the gas cells for them to rupture.

263 When using citric or α-ketoglutaric acid, the total quantity of CO₂ released during baking was significantly 264 lower than that in the control samples and barely differed from that from the samples containing only 265 NaHCO₃. These results indicate that in these samples high amounts of CO₂ had been produced and lost 266 during the mixing phase from the batters containing these acids, and thus even before the batter was 267 brought into the ERO. This was because a large amount of these acids dissolved in the aqueous phase of 268 the batter during mixing. Therefore, these acids can be categorized as fast-acting leavening agents. While 269 similar amounts of CO₂ were released during baking in the batters containing either citric or α -ketoglutaric 270 acid as in those containing only NaHCO₃, their height and CO₂ release profiles differed significantly from 271 those of the samples containing only NaHCO₃. Indeed, in these samples the batter height increased 272 significantly more during the early baking stage than when the batter contained only NaHCO₃, which 273 confirmed that a certain amount of CO_2 was still produced during the early baking stage. Whereas in the 274 cake batters containing slow acting leavening acids structure setting and the start of CO₂ release 275 coincided, in batters containing citric or α -ketoglutaric acid CO₂ release started after the start of structure 276 setting (cfr. Table 2). Likely, due to the high amount of CO_2 lost during mixing, insufficient CO_2 was 277 produced during the early baking stage (*i.e.* the beginning of structure setting) to ensure adequate 278 pressure buildup for gas cell opening. This shows that structure setting and gas cell opening not 279 necessarily occurred simultaneously. A certain amount of build-up pressure seems to be necessary in the

gas cells to open them, even when the structural parameters change due to structure setting. These results once again indicate the importance of the time of CO_2 release.

282 3.3. Conventional baking

The volumes of the cakes made from fumaric or adipic acid containing recipes were similar to those of the control cakes (Table 2 and Figure 4.1), indicating the usefulness of these acids for leavening cream cake systems. This was due to the similar CO_2 production before the cake structure had fully set (*cfr.* 3.2.). In line with what has been stated by different authors (Cepeda, Waniska, Rooney & Bejosano, 2000; Heidolph, 1996), fumaric acid holds promise as leavening acid in multiple bakery applications. Use of citric or α -ketoglutaric acids on the other hand, resulted in lower cake volumes as observed in the present ERO experiments (*cfr.* 3.2.).

Figure 4.2 shows the impact of the different leavening acids on the pH of the cake crumb. Cakes produced with SAPP₂₈ had a pH of 7.2-7.6. Evidently, cakes prepared without leavening acid were more basic pH (> 8.2). Cakes prepared with citric acid had a pH of 7.1-7.5, while cakes prepared with α -ketoglutaric acid had a pH of 7.5-7.9. The crumb of cakes made with fumaric or adipic acid showed so-called 'acidic hotspots' (Godefroidt *et al.*, 2019) spread over the crumb. This indicated that part of the baking acid had not fully reacted with NaHCO₃ and remained present in the final cake. Their presence also implied that the full CO₂ production potential had not been reached in these systems.

297 While the temperature of structure setting was not affected by the leavening acids, the crumb texture 298 was (*cfr*. Table 2). The use of fumaric $(10.5 \pm 1.0 \text{ N.cm}^3/\text{g})$ or adipic $(10.1 \pm 0.8 \text{ N.cm}^3/\text{g})$ acid resulted in 299 cakes that were as soft as the control cakes $(10.5 \pm 1.0 \text{ N.cm}^3/\text{g})$. However, cakes prepared with citric (14.4 300 $\pm 2.2 \text{ N.cm}^3/\text{g})$ or α -ketoglutaric $(14.5 \pm 1.7 \text{ N.cm}^3/\text{g})$ acid were firmer than control cakes, but not as firm 301 as the cake samples prepared without leavening acid $(18.0 \pm 2.5 \text{ N.cm}^3/\text{g})$. That denser cakes, which 302 evidently have a higher level of solid material per unit of volume, have higher crumb firmness is expected (Paraskevopoulou & Kiosseoglou, 1997). However, that the corrected firmness was higher for denser
 cakes (R² = 0.9975) implies that the different amounts and/or sizes of gas cells in these samples (indirectly)
 impacted the texture of the solid matter. Of note in this context is that incorporation of less gas cells leads
 to thicker cell walls (Zghal, Scanlon & Sapirstein, 2002).

307 These differences in cell wall structure were also reflected in the other cake texture parameters. Indeed, 308 while the use of fumaric, adipic, or α -ketoglutaric acid resulted in cake crumb with a springiness, 309 cohesiveness, and resilience, comparable to that of the control cakes, crumb of cakes prepared with citric 310 acid and that of cakes prepared without leavening acid had low springiness, cohesiveness, and resilience. 311 Multiple authors have linked springiness and resilience to the three-dimensional gel structure around the 312 gas cells in the crumb of pound cake (Paraskevopoulou & Kiosseoglou, 1997; Wilderjans et al., 2010). 313 Changes that (indirectly) alter said network structure, such as the presence of more or less gas cells in the 314 cake crumb, can presumably affect these parameters. There was indeed an inverse correlation between cake density and both springiness ($R^2 = 0.8199$) and resilience ($R^2 = 0.8755$). No such correlation could be 315 detected between cake density and cohesiveness. 316

317 4. Conclusion

318 The choice of leavening acid heavily influences cream cake quality by affecting how much CO₂ is produced during both mixing and/or baking. The fast-acting leavening citric and α -ketoglutaric acids mainly react 319 320 with NaHCO₃ during mixing, thereby releasing large amounts of CO_2 during this phase. The slow-acting 321 leavening acids SAPP₂₈, fumaric acid, and adipic acid, on the other hand, barely reacted with NaHCO₃ 322 during mixing. Thus, the majority of CO₂ production in cake batters containing these acids occurred during 323 the baking phase. That the density of all freshly mixed batter samples was equal showed that CO₂ 324 produced during mixing is not retained in the batter and that the use of fast acting baking acids in cream 325 cake systems therefore has little merit.

326 The ERO set-up used provided new insights regarding leavening agent functionality during baking. Fast-327 acting leavening acids resulted in low amounts of CO₂ production during baking, since the majority was 328 produced during mixing. As the latter was lost, this resulted in low volume and low quality cakes. 329 Significant leavening occurred during baking of batters prepared with the slow acting leavening acids. This 330 resulted in high volume and high quality cakes. Thus, not only the amount of CO₂ produced during baking, 331 but also the moment thereof played an important role in obtaining high quality cream cakes. Leavening 332 needs to occur before the cake structure has fully set, as evidenced by the differences between cakes 333 prepared with citric or α -ketoglutaric acid, and those prepared with only NaHCO₃. Large differences were 334 detected in cake volumes due to the difference in the time of CO_2 production. Compared to what was the 335 case in the control cakes, adipic acid use lead to a higher CO₂ production after the structure of the cake 336 had already set and therefore did not result in higher volume cakes.

In conclusion, an optimal leavening system for cream cake systems leads to release of the majority of its
 CO₂ during the first part of the baking phase, *i.e.* before structure setting has occurred. SAPP₂₈, fumaric
 acid, and adipic acid all performed similarly and resulted in the best cream cakes in terms of volume.

340 5. Acknowledgements

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346 *6. Author contributions*

The study was designed by Thibault Godefroidt, Nand Ooms, Kristof Brijs and Jan A. Delcour. Thibault Godefroidt collected the data. All authors contributed to the discussion on and interpretation of the results. The manuscript was drafted by Thibault Godefroidt, in close collaboration with Nand Ooms, and reviewed by all authors. Thibault Godefroidt, Nand Ooms, and Jan A. Delcour performed the final editing of the manuscript. 352 7. References

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- 436 **Table 1:** Cream cake batter ingredients on a 100 g flour (14.0% moisture content) base.
- 437 **Table 2:** Batter and cake parameters of recipes containing sodium acid pyrophosphate (SAPP₂₈), fumaric acid (FA),
- 438 adipic acid (AA), citric acid (CA), α-ketoglutaric acid (KGA), and samples without leavening acid. All measurements
- 439 were performed in triplicate. Standard deviations are indicated between parenthesis. Significantly different results
- 440 within one row are indicated by different letters ($\alpha = 0.05$). η_{RVA} = viscosity as measured with a rapid visco analyzer
- 441 (RVA), ΔH = enthalpy of the endothermic transitions.

Figure 1: Schematic representation of a closed electrical resistance oven (ERO) which heats cake batters without significant temperature gradients through Ohmic heating. The ERO is equipped with both a temperature (T) probe and a 100% carbon dioxide (CO₂) data logger to monitor the batter/cake temperature and the CO₂ release from the batter. The CO₂ data logger is coupled to the headspace of the ERO with filter tubes. Its input is applied to the side of the ERO, its output to the top. PID = proportional integral derivative.

Figure 2: Production of cake prepared with sodium acid pyrophosphate (SAPP₂₈) as leavening acid. Carbon dioxide (CO₂; % of gas phase) present in the electrical resistance oven (ERO) headspace, viscosity (η; Pa.s) as measured with a rapid visco analyzer (RVA), batter/cake height (cm), and temperature (T; °C) are all plotted in function of baking time (t; min). The temperature of onset of starch gelatinization and protein denaturation, as measured with differential scanning calorimetry (DSC), is indicated by T_o, while the peak temperature is indicated by T_p.

Figure 3: Baking profiles of cake prepared with sodium acid pyrophosphate (SAPP₂₈), fumaric acid (FA), adipic acid (AA), citric acid (CA), α-ketoglutaric acid (KGA), or without leavening acid. Carbon dioxide (CO₂; % of gas phase) present in the electrical resistance oven (ERO) headspace, viscosity (η; Pa.s) as measured with a rapid visco analyzer (RVA), batter/cake height (cm), and temperature (T; °C) are all plotted in function of baking time (t; min).

Figure 4: Cross-sections of cakes prepared with different leavening acids. (1) The height of the cakes are compared.
(2) The cross-sections of the cakes contain the pH indicator phenol red. The leavening acids were: sodium acid
pyrophosphate (SAPP₂₈), fumaric acid (FA), adipic acid (AA), citric acid (CA), α-ketoglutaric acid (KGA). Cake was also
produced with no leavening acid. The ruler on the right hand shows the color of phenol red solution in a pH 6.0 to
8.0 range.

Table 1:

Ingredient	Mass (g)		
Flour	100.0		
Sugar	89.0		
Rapeseed oil	58.0		
Egg white	43.1		
Egg yolk	24.6		
Water	43.5		
Emulsifier	1.9		
NaHCO ₃	1.1		
Leavening acid			
SAPP ₂₈	1.5		
<i>or</i> fumaric acid (FA)	0.7		
or adipic acid (AA)	0.9		
<i>or</i> α-ketoglutaric acid (KGA)	0.9		
or citric acid (CA)	0.7		

462	Table 2:
462	Table 2:

	SAPP ₂₈	FA	AA	СА	KGA	No acid
Batter density (g/cm ³)	1.04 (0.01) ^a	1.02 (0.01) ^a	1.02 (0.01) ^a	1.02 (0.01) ^a	1.04 (0.01) ^a	1.04 (0.01) ^a
Batter pH	6.80 (0.01) ^a	6.72 (0.04) ^{ab}	6.79 (0.06) ^a	6.65 (0.01) ^b	7.04 (0.01) ^c	7.46 (0.01) ^d
Cake weight (g)	206.2 (1.0) ^a	204.5 (0.5) ^a	206.8 (0.9) ^a	205.9 (1.2) ^a	205.2 (1.3) ^a	204.6 (1.4) ^a
Cake volume (cm ³)	394.8 (9.8) ^a	394.4 (6.0) ^a	398.5 (7.2) ^a	346.1 (12.0) ^b	350.5 (9.7) ^b	319.0 (11.5) ^c
Cake density (g/cm ³)	0.51 (0.01) ^a	0.51 (0.01) ^a	0.51 (0.01) ^a	0.58 (0.02) ^b	0.58 (0.02) ^b	0.64 (0.03) ^c
Crumb springiness (%)	83.0 (0.4) ^a	83.2 (0.7) ^{ab}	83.9 (0.4) ^b	81.5 (0.6) ^c	82.7 (0.6) ^a	80.9 (1.0) ^c
Crumb cohesiveness (%)	60.5 (1.0) ^{ab}	60.1 (0.5) ^a	61.0 (0.5) ^b	59.2 (1.0) ^c	61.7 (0.6) ^b	58.9 (1.1) ^c
Crumb resilience (%)	19.5 (0.9) ^{ab}	19.9 (0.4) ^a	20.3 (0.8) ^a	17.2 (0.9) ^c	18.6 (0.8) ^b	16.5 (1.2) ^c
Corrected firmness (N*cm ³ /g)	10.5 (1.0) ^a	10.5 (1.0) ^a	10.1 (0.8) ^a	14.4 (2.2) ^b	14.5 (1.7) ^b	18.0 (2.5) ^c
T of η _{RVA} increase (°C)	88.4 (0.8) ^a	88.2 (1.0) ^a	88.4 (1.6) ^a	89.1 (0.8) ^a	89.2 (0.5) ^a	87.9 (3.0) ^a
T_o of DSC endotherm (°C)	88.6 (0.9) ^a	87.8 (1.2) ^a	88.1 (0.5) ^a	88.6 (0.4) ^a	88.5 (1.2) ^a	87.7 (1.5) ^a
T _p of DSC endotherm (°C)	96.2 (1.1) ª	95.5 (1.5) ^a	95.8 (1.0) ^a	95.9 (0.6) ^a	96.9 (1.3) ^a	95.9 (1.8) ^a
ΔH of DSC endotherm (J/g)	2.57 (0.23) ^a	2.52 (0.10) ^a	2.52 (0.36) ^a	2.36 (0.36) ^a	2.67 (0.29) ^a	2.74 (0.25) ^a













471 Figure 4:

