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Ohmic baking of gluten free sponge cake: Analysis of technological and quality characteristics

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ABSTRACT

The demand of gluten-free bakery products is worldwide increasing. Simultaneously, ohmic heating is an alternative heating technology that still deserves further research and development. Therefore, the aim of this work was assessing different technological and quality characteristics of gluten free sponge cake baked by ohmic heating. A custom ohmic system was designed and built and different electric field strengths (1500, 2000 and 2500 V/m) were tested. Conventional baking was performed for comparison purposes. The conventional baking time was 24 min, whilst the ohmic heating time ranged from 3.51 min at 2500 V/m to 7.93 min at 1500 V/m. The ohmic system achieved significantly higher energy efficiencies, reaching nearly 60%, compared to only 4.1% for conventional baking. Additionally, specific energy consumption was significantly lower for ohmic heating. Weight loss was higher for ohmically processed samples, showing larger number of pores in their inner spongy structure. Ohmic heating resulted in a larger volume expansion and a cake with lower density. The remaining quality characteristics, such as color, hardness, cohesiveness, and elasticity, were not significantly different. Results demonstrated that ohmic heating is a suitable technology for baking gluten-free sponge cakes and that it is a promising technology for fast industrial baking of such products.

1. Introduction

There is currently an increasing demand for gluten-free bakery products from groups with celiac disease, other gluten-related allergies, or health consciousness. In the production of gluten free (GF) bakery goods, the main technological and quality challenges are the poor gas retention and low volume of the final product, aspects that influence its acceptance (Naqash, Gani, Gani, & Masoodi, 2017). Several studies have attempted to overcome these drawbacks by adopting different strategies, mainly focusing on formulation, which involves the incorporation of additional ingredients to counteract gluten deficiency (Marchetti, Acuña, & Andrés, 2021; Xu, Zhang, Wang, & Li, 2020) or the use of different aeration methods to improve gas incorporation and stabilization (Elgeti, Jekle, & Becker, 2015). In addition to these, the selection of the baking method, including the optimization of baking conditions, can help to improve the overall quality of this product category.

One of the most recent and promising technological approaches is the use of ohmic heating (OH) (Waziiroh, Schoenlechner, Jaeger, & Bender, 2022). Ohmic heating is a nonconventional heating technology based on the internal generation of heat by passing an electrical current through a medium with electrical resistance, such as a food (Joule effect, Sakr & Liu, 2014). Unlike conventional heating methods, where heat is transferred from a surface or a hot environment to the inner regions of the food by convection, conduction and radiation, OH generates heat volumetrically throughout the material, i.e., uniformly throughout the food (Marra, Zell, Lyng, Morgan, & Cronin, 2009). Among the main advantages of this technology are faster and uniform heating, shorter heating times, low energy consumption improving thus energy efficiency, thus placing OH among those considered environmentally friendly (Sakr & Liu, 2014; Sastry, Heskitt, Sarang, Somavat, & Ayotte, 2016), which can contribute to food processing sustainability (Marra, 2023).

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Several studies have reported on the potential of OH in food processing (Alkanan, Altemimi, Al-Hilphy, Watson, & Pratap-Singh, 2021), but few research have focused on baked goods. Recently, some works have been reported applying this technology to the baking of GF bread (Masure, Wouters, Fierens, & Delcour, 2019; Bender et al., 2019; Waziiroh, Bender, Jäger, & Schönlechner, 2023; Waziiroh, Bender, Saric, Jaeger, & Schoenlechner, 2021; Waziiroh et al., 2022) and the baking of whipped mixture for cakes (Deleu et al., 2019; Khodeir et al., 2021). These studies confirmed that OH is superior to the conventional baking method in terms of reducing baking times and energy consumption. However, the effect of OH on the overall product quality (texture, color, crumb properties, porosity, among others), and -particularly- the influence of the process variables, need further research. Therefore, the objective of this work was to investigate the potential of OH as an alternative and novel approach for baking GF sponge cake. For this aim, a lab OH cell was built to perform the baking tests, at three different electric fields (1500, 2000 and 2500 V/m). From these tests, baking times, weight loss, energy efficiency, and several quality characteristics (moisture content, crumb density and porosity, color, texture) were measured, and compared with conventional baking. These trends will help us to improve OH baking, focused on different technological and quality aspects of both the process and the product.

2. Materials and methods

2.1. Batter preparation

The batter was prepared from a commercial gluten-free premix (Exquisita, Molinos Río de La Plata S.A., Argentina) using the following recipe: 450 g of premix, 200 g of whole milk and 150 g of whole fresh egg. All ingredients were beaten at constant speed for 5 min. The final batter composition was about 44.8 g/100g carbohydrates, 3.1 g/100g proteins, 5.6 g/100g fat, 1.7 g/100g ashes and 44.8 g/100g moisture.

2.2. Ohmic baking

2.2.1. Experimental OH cell

A lab scale OH cell was designed and constructed ad-hoc (Fig. 1a and b), being its internal dimensions 9 × 9 × 10 cm (wide, depth, height). Two electrodes (9 cm × 10 cm) made in stainless steel 316, thick 2 mm, where held 9 cm far one from each other in an acrylic container built as described in Fig. 1. The acrylic walls were 10 mm thick. In Fig. 1, it is possible to appreciate a centimeter ruler allowing a direct estimation of dough height (and thus volume) change during the cooking process and how easy the OH cell can be disassembled and the position of connectors to the power supplier (Fig. 1b).

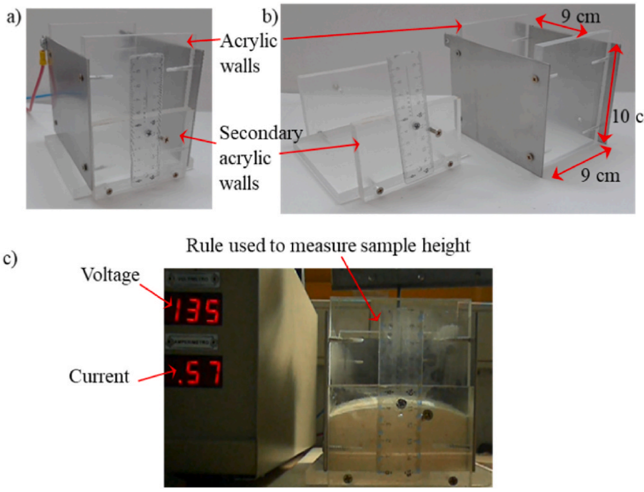

Fig. 1. a) Ohmic cell built for the baking tests. b) Image of the cell disassembled. c) Frame of one of the videos used to measure current intensity, voltage and sample height during baking.

2.2.2. Ohmic baking tests

The baking tests were carried in the OH cell connected to a circuit supplied with AC current at 50 Hz and at a maximum voltage of 225 V (El Toroide, Argentina). To avoid a high initial current density, which could induce water vaporization, the electric potential started from 0 (Icier & Illicali, 2004). So, the applied voltage was increased (manually) from 0 to the final value, with a slope of about 220 V/min. Three levels of electric field strength were tested: 1500, 2000 and 2500 V/m, which corresponds to 135, 180 and 225 V respectively. The rheostat allows increasing the domestic power supply voltage above 220 V to reach an electric field of 2500 V/m.

For the tests, 113.7 g (±1.1 g) of batter was poured into the ohmic cell, equivalent to an initial height of 15 mm. As the sample undergoes a large expansion during baking, this initial height prevents the product overflowing at the end of baking.

During the baking tests, the internal sample temperature was recorded every 5 s using a J thermocouple (OMEGA, USA), connected to a data recorder (Novus Field Logger, Brasil). Only one sensor was used to diminish the sample perturbation which could affect the quality attributes of the baked product. Also, the surface temperature was measured with a thermographic camera (TESTO 875, Germany) every 30 s. To check that the electrical current does not affect the thermocouple measurements, a set of preliminary tests were done using simultaneously the thermocouple and a fiber optic sensor (FISO Technol. Inc, Canada), being the average temperature difference between instruments 2.5%. Additionally, a video (320 × 640 pixels, 30 FPS) of each baking test was recorded using a digital camera (Coolpix P610, Nikon, Japan). Afterward, the video was read using an ad hoc script developed in MATLAB (The MathWorks Inc., USA, version 9.2 R2017a). This script shows the video frames at selected time intervals and pauses it, allowing the user to register the electrical current (A), the voltage (V) (both measured and indicated in the front panel of the rheostat, Fig. 1), and the sample height; then pressing any key the script show the next video frame and so on, until the end of the process.

The ohmic baking was finished when the measured temperature reached 95 °C (Ureta, Goñi, Salvadori, & Olivera, 2017).

2.2.3. Conventional baking

For comparison purposes, a conventional heating CH test was performed. An electric domestic oven was employed (Ariston FM87-FC, Italy) using the natural convection mode at 180 °C. A container with the same dimensions that the ohmic cell was used to account for the same initial mass and height. During cooking the inner and ambient temperature were recorded. The baking was also finished when the inner temperature reached 95 °C. After baking, the same quality characterization as the ohmic baked samples were performed (see Section 2.4).

2.3. Energy consumption and efficiency

First, at the end of baking, the sample weight loss was measured:

$$WL(\%) = 100\left(\frac{m_i - m_f}{m_i}\right) \tag{1}$$

where m is the sample mass (kg) and subscripts i and f refer to initial and final condition, respectively. Then, the amount of energy needed to the cake (cake energy consumption, CEC, kJ) is given by a sensible heat and a latent one, related to moisture leaving the system as vapor:

$$CEC = m_i\left(C_P\left(T_f - T_i\right) + \frac{WL(\%)}{100}\lambda\right) \tag{2}$$

where C_P (kJ/(kg °C)) is the average sample heat capacity in the range of temperature the sample undergoes to, T is sample temperature (°C), λ is vaporization heat of water (kJ/kg). For calculation purposes, it is assumed that all the sample volume is at the same recorded temperature, for both baking methods. This is certainly more appropriate for ohmic baking since the volumetric nature of heating (Derde, Gomand, Courtin, & Delcour, 2014), although a thin layer on the surfaces in contact with the walls and air are at lower temperature. Temperature in these regions was not measured but can be visually asserted. For conventional baking the sample surface temperature can attain higher values, but the crust thickness is low, and most of crumb is close to phase change temperature at the end of baking.

The ohmic energy consumption (*OEC,* kJ) was defined as the total energy consumed by the ohmic cell and it was computed by numerical integration (trapezoidal rule) of the power consumed by the cell during the time (Sakr & Liu, 2014):

$$OEC = \frac{1\ kJ}{1000\ J} \sum_{n=1}^{N-1} 0.5(P_n + P_{n+1})\Delta t \tag{3}$$

where P_n ($P_n = I_n\ V_n$) is the power (W) at time n; I_n and V_n are the electric current (in A) and voltage (V) at time n, and N is the total number of experimental points.

The energy efficiency was obtained as the ratio between both energies:

$$\eta\ (\%) = 100 \frac{CEC}{OEC} \tag{4}$$

The conventional oven energy consumption (*COEC*, kJ) was estimated from the oven temperature profile (Ureta et al., 2017), and the efficiency was defined similarly to Eq. (4), as the ratio *CEC*/*COEC*.

Additionally, the specific energy consumption for ohmic and conventional baking was calculated, which provides the energy required by unit mass of product (kJ/kg):

$$SEC = \frac{(OEC)\ or\ (COEC)}{m_i} \tag{5}$$

2.4. Quality characterization of sponge cake

2.4.1. Moisture content

The moisture content of the crumb was determined by drying 5 g of sample in a stove at 105 °C, until constant weight was achieved. Also, the moisture content of raw batter was measured. Four replicates were made for each tested condition.

2.4.2. Crumb density

To calculate the crumb density the baked sample was cut into 10 mm slices, discarding the external layers; from each slice several 25 mm diameter cylinders were obtained using a sharp mold. Each cylinder was weighed, the diameter and height were verified with a caliper, and then density was calculated as the quotient between mass and volume (Ureta, Olivera, & Salvadori, 2014). On average, 12–15 cylinders per sample were used, and 1 sample for each baking condition.

2.4.3. Final height

The final height was defined as the one recorded at the central point of the sample. For OH, selected frames of the video were used for this aim. For conventional baking, the sample was removed from the container, and a picture was taken together a ruler, for size reference.

2.4.4. Texture properties

Textural properties of crumb were determined using a CT3 texture analyzer (TPA-CT3, Brookfield Engineering Labs. Inc., UK) performing a Texture Profile Analysis - TPA (Olivera & Salvadori, 2006). TPA is mostly used to evaluate the texture of breads and cakes (Guiné, 2022). Crumb cylinders (10 mm height and 25 mm diameter) were compressed twice with a TA4/1000 probe, doing penetration cycles at a speed of 1 mm/s over a compression ratio of 40%. Crumb texture parameters such as hardness, cohesiveness, and elasticity were recorded with Texture Pro CT V1.6 (Brookfield Engineering Labs. Inc., UK). Twelve replicates were performed for each baking condition.

2.4.5. Crumb porosity

Porosity is defined as the pore volume related to the total sample volume (Kumar Jha, Chevallier, Cheio, Rawson, & Le-Bail, 2017). Often in bread and other baked goods, the crumb porosity is estimated as a bidimensional property, from image analysis (Rathnayake, Navaratne, & Navaratne, 2018; Ureta et al., 2014); this way of measuring works well with comparison purposes. After baking, the sample was sliced at the half-depth and a digital image of the cross section was taken using a scanner (HP 4500 Hewlett Packard, Palo Alto, CA, USA), together with a ruler for size calibration. The 200 dpi RGB images were processed using a MATLAB script (Image Processing Toolbox, The MathWorks, USA). The images were transformed to grayscale, then a histogram equalization was performed, and finally were segmented into binary images using a threshold: pixels below this threshold were assigned to the pore region, and above this value were assigned to crumb.

The number of pores in the image (dark regions) per unit area (Ureta et al., 2014) and their size distribution were obtained. Wang, Karrech, Regenauer-Lieb, and Chakrabati-Bell (2013) proposed a Weibull function to describe the pore size distribution of bread; similarly, Rahimi, Baur, and Singh (2020) obtained a Weibull-like distribution of pore size. So, the pore size values obtained in this work was fitted to a Weibull distribution:

$$f(x) = \alpha\beta^{\alpha}x^{\alpha-1}e^{-(bx)^{\alpha}} \tag{6}$$

where x is the pore area (mm^2), and α, β are unknown parameter. These values were fitted by non-linear regression using the *lsqcurvefit* MATLAB *function*. From α and β, the average pore area and their variance were obtained.

2.4.6. Color

The surface and inner sample color was measured by means of a computer vision system (CVS). This CVS consisted of an image acquisition chamber with four fluorescent lamps, inside of which the sample was placed together a color pattern chart (Color Checker Passport, XRite, USA, with known $L^*a^*b^*$ values). So, a picture is taken and the *RGB* color of the sample it transformed to the $L^*a^*b^*$ color space, using the color chart as the calibration reference (Goñi & Salvadori, 2017). A simple software developed in MATLAB is used for the conversion and measurement process (Goñi & Salvadori, 2015).

2.4.7. SEM

A scanning electron microscope (SEM, FEI Quanta 200, Hillsboro, Oregon, USA) was used to observe the microstructure of the crumb samples obtained for the different OH conditions, and also to examine the minerals on the samples surfaces with energy-dispersive X-ray spectroscopy (EDS). The samples were dried at the critical point, mounted on pieces of aluminum using double-sided tape and vacuum coated with a gold film (Argel et al., 2022). Two replicates of each condition and at least five representative fields were obtained from each replicate.

2.5. Statistical analysis

The results were expressed as the mean ± the standard deviation. The significance of differences between the means was determined by the analysis of variance ANOVA followed by the Tukey multiple-comparison test. A comparison of means was carried out at a 5% level of significance ($p<0.05$).

3. Results and discussion

3.1. Process parameters behavior

Fig. 2a shows the evolution of the voltage during the OH tests. The required electric field set point of 1500, 2000 or 2500 V/m, were reached linearly in about 0.62, 0.82 and 1 min, respectively, and then it remains constant until the end of the test. When electric potential increases from 0 to final value, the electric current intensity increases linearly as expected (Fig. 2a and b, short times). Afterward, when electric potential remains constant, the electric current intensity first increases toward a maximum value and then it decreases (Fig. 2b). This is due to the temperature dependence of the electrical conductivity of batter components (Li, Li, Li, & Tatsumi, 2004; Wang & Sastry, 1997) and its changes due to the processing conditions. As temperature increases electrical conductivity increases, and consequently higher electric current intensity flows. When core temperature reaches about 70–80 °C (Fig. 2c, blue, green and red lines for electric field strength of 1500 V/m, 2000 V/m, and 2500 V/m, respectively), the electric current starts to diminish, which can be related to starch gelatinization. When gelatinization takes place the batter (liquid) is gradually transformed into crumb (a porous solid), starch granules increase their hydration: free water is gradually transformed to bound water and electron mobility decreases, so electrical conductivity decreases (Subbiah & Morison, 2018; Wang & Sastry, 1997). Later, energy is used to evaporate water, which diminishes the water content and the electrical conductivity, and then the electric current intensity diminishes gradually (Kulishov, Kulishova, Rudometova, Fedorov, & Novoselov, 2020).

Fig. 2c shows the temperature profiles of the crumb and the upper surface for the different OH conditions. The results show that increasing the applied electric field increase the heating rate. In a first instance, the baking time was defined as the time to reach crumb temperature equal

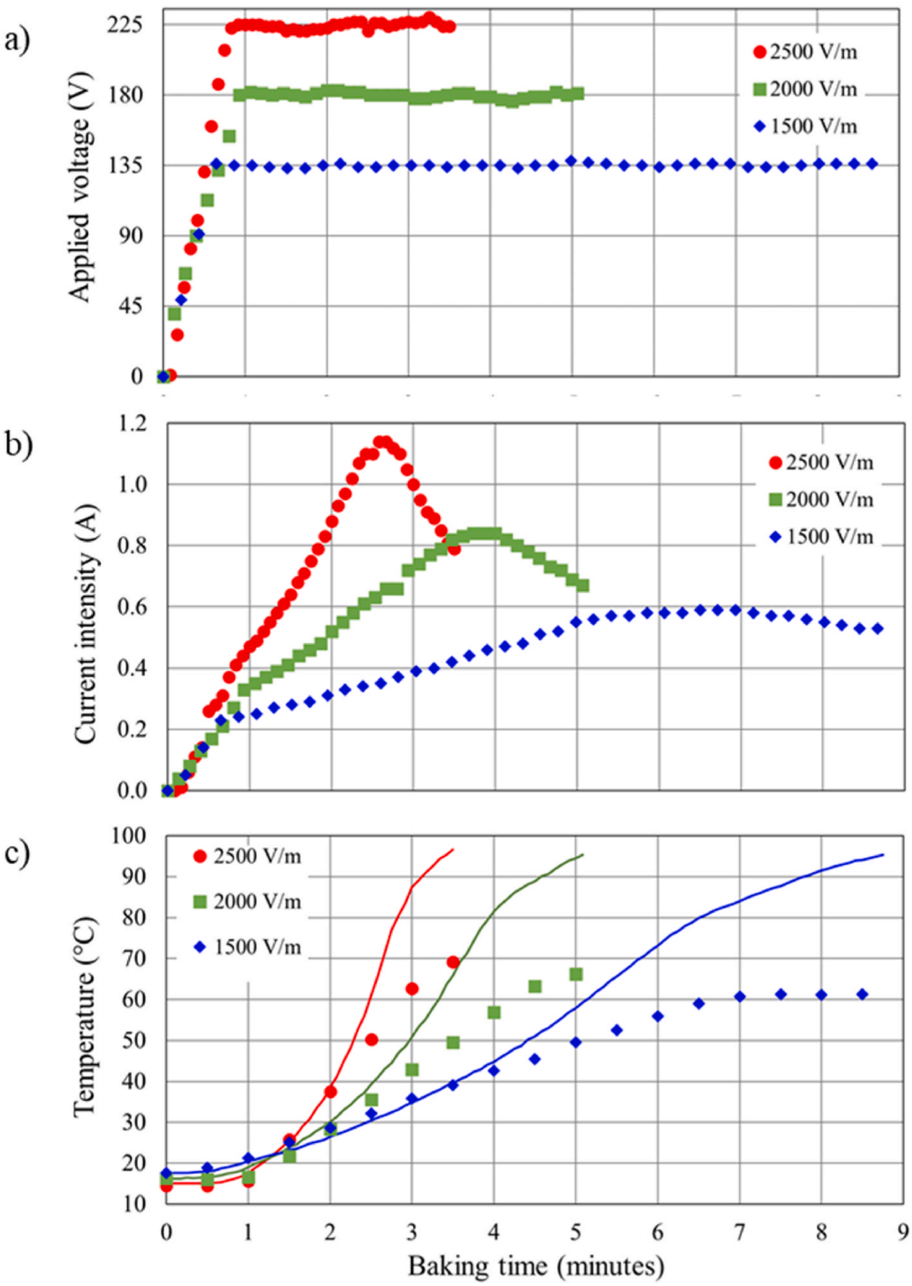

Fig. 2. Evolution of a) voltage (V); (b) current intensity (A); (c) crumb (lines) and surface temperature (symbols); vs. ohmic baking time at different electric field strengths.

to 95 °C (BT1). These times was, in average, 7.93, 4.75, and 3.51 min, at 1500, 2000, and 2500 V/m, respectively (Table 1). The equivalent process in conventional baking takes 24 min, being this time 3.03, 5.05 and 6.84 larger respect to OH at 1500, 2000 and 2500 V/m, respectively.

However, at these OH baking times the upper surface did not reach the temperature due to the colder ambient air and cell walls (Fig. 2c, symbols). Although it is a behavior restricted to a thinner region near the surface, affects the sample appearance. Derde et al. (2014) found very small temperature differences (lower that 2.8 °C) inside bread during OH, except at the top surface, where differences near 13 °C were found. In a hypothetic industrial design, this problem could be easy solved by adding a final radiative heating on the product surface, to brown it at desired level. In any case, we decide to extend the baking tests until a fully baked top surface was achieved (visually loss of the wet appearance). In preliminary tests, this time was found to be close to twice that required to obtain crumb temperature of 95 °C. So, a new set of baking tests were performed (BT2). Despite this, OH heating times were significantly lower than conventional baking ones.

As expected, weight loss was affected by the duration of the process and the baking method used. The weight loss is mainly due to moisture evaporation from baked dough. The evaporation is promoted by a difference of water concentration in the vapor phase, at the evaporation surface and in the surrounding environment. The moisture that is transferred in the vapor phase comes from the dough core. The transfer of moisture from the dough core toward its surface is promoted by mechanisms all characterized by long characteristic times: usually, the resistance to evaporate from the surface toward the external environment is lower than the resistance to diffuse from the core toward the external surface. So, the longer the process, the high the number of water molecules that can complete they journey toward the evaporation surface, and then the higher the weight loss due to evaporation. Longer process times and the formation of a dehydrated surface crust led to greater weight loss in conventional baking compared to ohmic baking, resulting in a lower yield for the former (Table 1).

On the other hand, the moisture content of ohmic baked crumbs was significantly lower at BT1 and more noticeable at BT2 than in conventional baking (Table 1). Due to the volumetric heating mechanism of ohmic baking, the vapor is generated in the whole sample from the beginning of baking. Also, due to the absence of a dehydrated surface crust, the water vapor generated in the center of the product condenses on the cooler outer surface of the sample, from where it can evaporate more quickly. This phenomenon facilitates water evaporation, reduces crumb moisture content (compared to conventional baking) and produces a wet surface. In addition, when OH was continued to obtain a fully cooked top surface (BT2), the moisture content of the crumb decreased as a function of the processing time (Table 1), since most of the energy is used to water evaporation. So, an additional characteristic of OH is that a control of crumb humidity could be attained. On the contrary, in conventional baking crumb humidity is barely lower than the raw sample, which is due to the evaporation-condensation-diffusion mechanism (Purlis & Salvadori, 2009; Ureta et al., 2019).

The analysis of technological aspects of OH baking and quality characterization of baked GF sponge cake detailed in the following sections, was done using BT2 condition.

Table 1
Baking technological parameters[#].

	Ohmic baking			Conventional
	1500 V/m	2000 V/m	2500 V/m	
BT1, T crumb = 95 °C				
Baking time (min)	7.93 ± 0.42^{a}	4.75 ± 0.29^{b}	3.51 ± 0.16^{c}	24.0 ± 2.61^{d}
Weight loss (%)	3.00 ± 0.24^{a}	2.81 ± 0.11^{a}	2.46 ± 0.01^{b}	13.75 ± 0.01^{c}
Crumb moisture (g/100 g)	33.08 ± 0.18^{a}	34.56 ± 0.50^{b}	35.53 ± 0.32^{c}	39.77 ± 0.13^{d}
BT2: Baking time double to BT1				
Baking time (min)	17.06 ± 0.51^{a}	9.56 ± 0.59^{b}	7.28 ± 0.25^{c}	–
Weight loss (%)	8.36 ± 0.02^{a}	6.73 ± 0.94^{b}	5.81 ± 0.08^{b}	–
Crumb moisture (g/100 g)	25.01 ± 0.86^{a}	28.81 ± 1.97^{b}	30.42 ± 1.20^{b}	–

[#] Values expressed mean ± standard deviation. Different letter in the same row indicates significative differences ($p < 0.05$).

3.2. Energy consumption and efficiency

To calculate the *CEC*, heat capacity of 2.9 kJ/(kg °C) was estimated from the sample composition and temperature (Choi & Okos, 1986); an average value between initial temperature and water phase change temperature was used. For OH the estimated energy efficiencies were between 58.9 and 62.8 % (Table 2); not significative differences were found between different electric fields. These values are similar to previous published efficiency values for other products. During heating of coffee grains, Sagita et al. (2022) found efficiency values between 54.2 % and 95.7 %; lower values were produced at low sample sizes and electric fields since long times are required and a large loss of energy to the ambient is observed. Icier and Ilicali (2005) measured efficiency by a system efficiency coefficient and obtained values between 0.52 and 0.92 during heating of concentrated orange juice. In the cooking of noodles, Jo and Park (2019) found a system efficiency coefficient between 0.46 and 0.63.

The materials of the ohmic cell (steel electrodes and acrylic) also are heated, so efficiency is expected to be higher than the calculated values. A simple assumption about the average temperature of such materials is not easy, so were not included in calculations. The conventional baking has much lower energy efficiency, because of the small sample mass used. In a real situation, when bigger samples are used, the energy efficiency would be higher; for instance, up to 8–10 trays could be put in the oven, so energy efficiency is expected to increase in a similar proportion, but still below the efficiency of the ohmic cell. During combined bread baking, Panirani, Darvishi, Hosainpour, and Behroozi-Khazaei (2023) found low energy efficiency using hot air at 200 °C and ohmic heating, 15.55 %, even worse that using only hot air (17.36 %). It was attributed to the moisture lost at the beginning of baking due to the ohmic source, which produces high porosity and low thermal conductivity, retarding the heating; also, electrical contact malfunctioning was reported which affect the ohmic heating source.

Such differences in energy efficiencies influence accordingly on the specific energy consumption, being much lower for ohmic heating. In Table 2 the *SEC* for OH diminish as electric field increases. Such values are obtained for BT2 condition, near 50 % correspond to sensible heat and 50 % to water evaporation. In BT1 condition, *SEC* ranged from 255.1 to 299.1 kJ/kg, and most of the required energy correspond to sensible heat.

For bakery products reported *SEC* have an average value of 5210 kJ/kg (Ladha-Sabur, Bakalis, Fryer, & Lopez-Quiroga, 2019), but large variation exists, depending on the product type, heating device, etc. Ureta et al. (2017) found specific energy consumptions between 3209 and 5340 kJ/kg during conventional sponge cake baking. The samples used in the current work were similar to Ureta el at. (2017), but the

Table 2
Energy efficiencies and specific energy consumptions[#].

	Ohmic baking (BT2)			Conventional
	1500 V/m	2000 V/m	2500 V/m	
η (%)	61.1 ± 5.4^{a}	58.9 ± 3.6^{a}	62.8 ± 4.6^{a}	4.1 ± 0.3^{b}
SEC (kJ/kg)	634.9 ± 67.2^{a}	622.2 ± 21.5^{a}	525.1 ± 20.5^{b}	8299.3 ± 970.9^{c}

[#] Values expressed mean ± standard deviation. Different letter in the same row indicates significative differences ($p < 0.05$).

sample size is lower, so higher *SEC* were obtained.

3.3. *Quality characterization of sponge cake*

Generally, due to chemical leavening agents, this type of product undergoes significant volume expansion during baking (Godefroidt, Ooms, Bosmans, Brijs, & Delcour, 2021). Fig. 3a shows images of the OH cell to illustrate the evolution of the sample height at different baking times at 2500 V/m. Also, Fig. 3b shows the evolution of the sample height during baking under different electric field conditions. In all cases there is a lag phase followed by a gradual increase until the final stabilization value. The time of the lag phase and the height evolution are highly dependent on the applied field, i.e. as the electric field increases, these times decrease.

Fig. 3b further shows that, during OH, the sample goes from the initial height of 1.5 cm to a final value of 5.6, 6.1 and 6.4 cm for 1500, 2000 and 2500 V/m, respectively. For conventionally baked samples, the final height was significantly lower, 4.6 cm. This behavior could be attributed to the fact that, as the dehydrated surface crust typical of baked products is not formed in OH, the expansion of the product is favored.

Table 3 shows the different quality characteristics obtained for the products baked at the different conditions of OH and CH. Firstly, the results obtained indicated that OH produces significantly less dense crumbs than CH. Moreover, the applied electric field did not influence this parameter, resulting in average 212.2 kg/m^3. The lower crumb density could be correlated with the higher expansion of the ohmic baked sample compared to the conventional one. In addition, the lower moisture content would also contribute to this behavior.

In terms of texture, despite the differences found in crumb porosity and density, no significant differences ($p > 0.05$) were found in the TPA tests in terms of hardness, cohesiveness and elasticity of the crumb obtained by CH and OH at higher and moderate electric fields (Table 3). On the contrary, in OH at 1500 V/cm, the crumbs were harder, less elastic, and less cohesive, possibly due to the high dehydration of the crumb (Table 1) under these conditions. Similar results were reported by Deleu et al. (2019).

The lack of dehydrated surface in OH is also evident in the surface color values, similar to those referred to the crumb (Table 3). On the other hand, the surface color of CH is significantly different, characterized by a lower brightness L* and a more developed color (a*, b*). This disadvantage of OH could be overcome by using combined methods

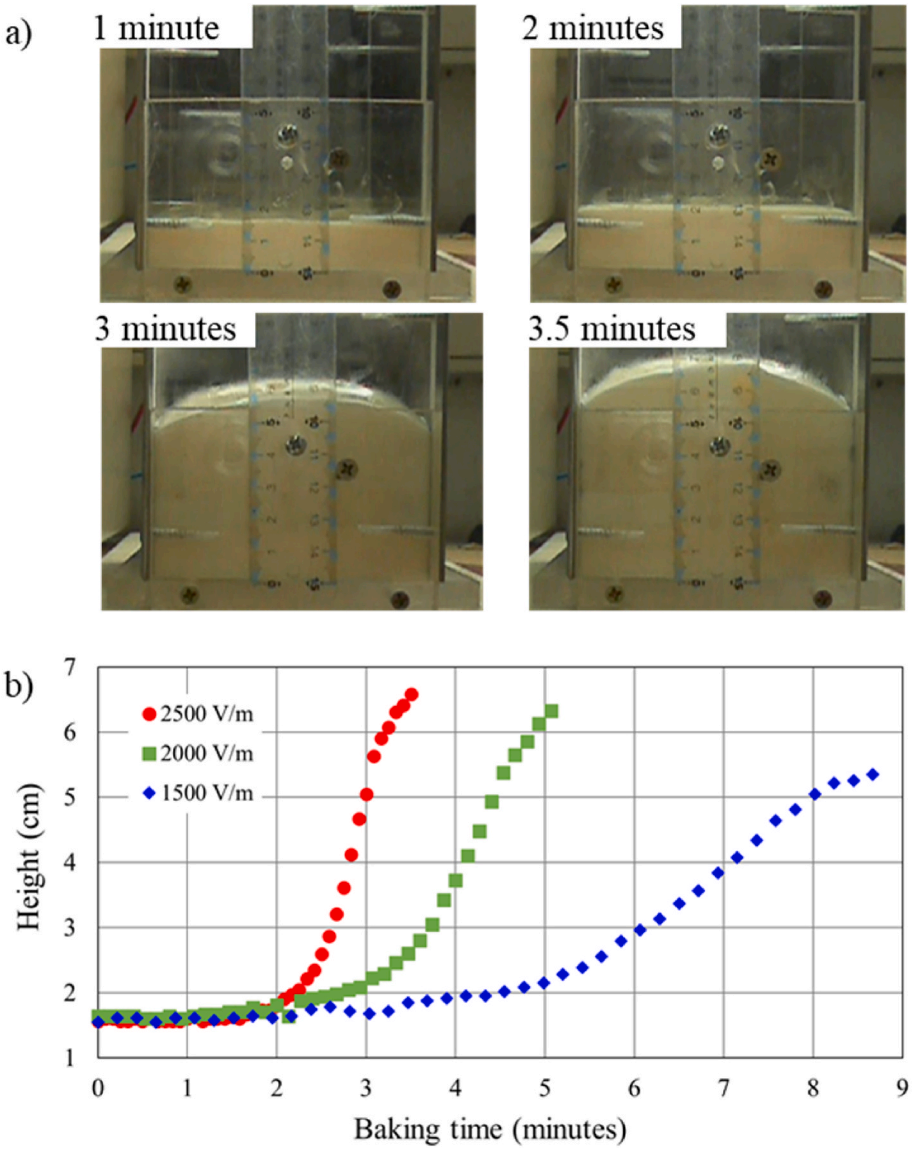

Fig. 3. a) Images of ohmic baking at 225 V and different times. b) Central cake height vs. time obtained by image processing for different electric fields. The behavior of a sample is depicted, which is representative of all samples.

Table 3
Quality characteristics of sponge cake.

	Ohmic baking (BT2)			Conventional
	1500 V/m	2000 V/m	2500 V/m	
Crumb density (kg/m^3)	214.7 ± 34.2^{a}	199.2 ± 23.1^{a}	222.7 ± 27.6^{a}	312.2 ± 21.7^{b}
Hardness (N)	2.48 ± 0.20^{a}	1.95 ± 0.30^{b}	1.85 ± 0.22^{b}	1.77 ± 0.26^{b}
Cohesiveness	0.62 ± 0.02^{a}	0.69 ± 0.02^{b}	0.72 ± 0.03^{b}	0.70 ± 0.02^{b}
Elasticity	0.84 ± 0.02^{a}	0.89 ± 0.03^{b}	0.92 ± 0.03^{b}	0.91 ± 0.03^{b}
Batter color				
*L**	84.1 ± 1.5			
*a**	0.8 ± 0.3			
*b**	24.7 ± 0.6			
Crumb color				
*L**	88.5 ± 2.7^{a}	89.8 ± 2.7^{a}	87.5 ± 3.3^{a}	84.3 ± 3.4^{a}
*a**	−1.8 ± 0.7^{a}	−0.9 ± 0.7^{a}	−0.9 ± 0.8^{a}	−0.4 ± 0.9^{a}
*b**	19.8 ± 3.3^{a}	21.3 ± 3.4^{a}	21.1 ± 3.9^{a}	25.9 ± 3.2^{a}
Top surface color				
*L**	84.6 ± 4.9^{a}	81.3 ± 7.2^{a}	81.2 ± 6.5^{a}	69.8 ± 11.7^{b}
*a**	−0.1 ± 1.1^{a}	1.4 ± 1.5^{a}	0.4 ± 1.4^{a}	15.3 ± 6.2^{b}
*b**	27.8 ± 3.7^{a}	27.8 ± 3.2^{a}	27.9 ± 2.5^{a}	45.6 ± 7.2^{b}

*Values expressed mean ± standard deviation. Different letter in the same row indicates significative differences ($p < 0.05$).

by adding a short hot air treatment to OH. In this sense, recently Panirani et al. (2023) developed a bread baking system using different combinations of conventional, ohmic and infrared methods in parallel. Additionally, often a main component of sponge cake is the topping (Pycarelle, Brijs, & Delcour, 2020), which overcomes such disadvantage. The lack of characteristic color can be more determinant for bread or foodstuffs without topping.

Fig. 4 a-d show the scanned sample slices and result of image processing. Clearly visually the conventional baked sample have less pore count, and large size pores. For OH samples, the pore count augments with electric field intensity, and simultaneously the pore size diminishes. Table 4 show calculated values from image processing; respect to CH, OH have 25.9, 75.5 and 108.9 % more pore by area for 1500, 2000 and 2500 V/m, and pore average area diminish 8.9, 31.8 and 36.8 % for the same electric fields.

In Fig. 4e the pore area histogram is depicted; in relative terms, the OH provides samples with a larger proportion of small pores, whereas the conventional baked sample have a higher proportion of large pores.

Fig. 5 shows images taken at 1000x magnification of crumb baked in conventional and ohmic ovens. In conventional baking (Fig. 5a) the deformation of the starch granules is more noticeable. The gelatinized starch granules were distributed on the surface of the sample and appeared as continuous sheets. On the other hand, in the crumb baked in the ohmic oven, granule residues and deformed starch structure were observed together (Fig. 5 b-d). Not all starch granules lost their identity and disintegrated completely. In ohmic heating, incomplete gelatinization may occur due to the higher heating rate and moisture loss.

Distribution of elements and their contents of OH and CH samples were evaluated by SEM-EDX of cross-section. Based on SEM-EDX, it was found that carbon (48.17–58.74 %) and oxygen (40.94–51.62 %) constituted the major constituents in all studied samples. This test did not detect any elements that could be caused by electrode corrosion such as iron, nickel, or chromium. These results are therefore encouraging to continue the sensory characterization of the product obtained by ohmic baking.

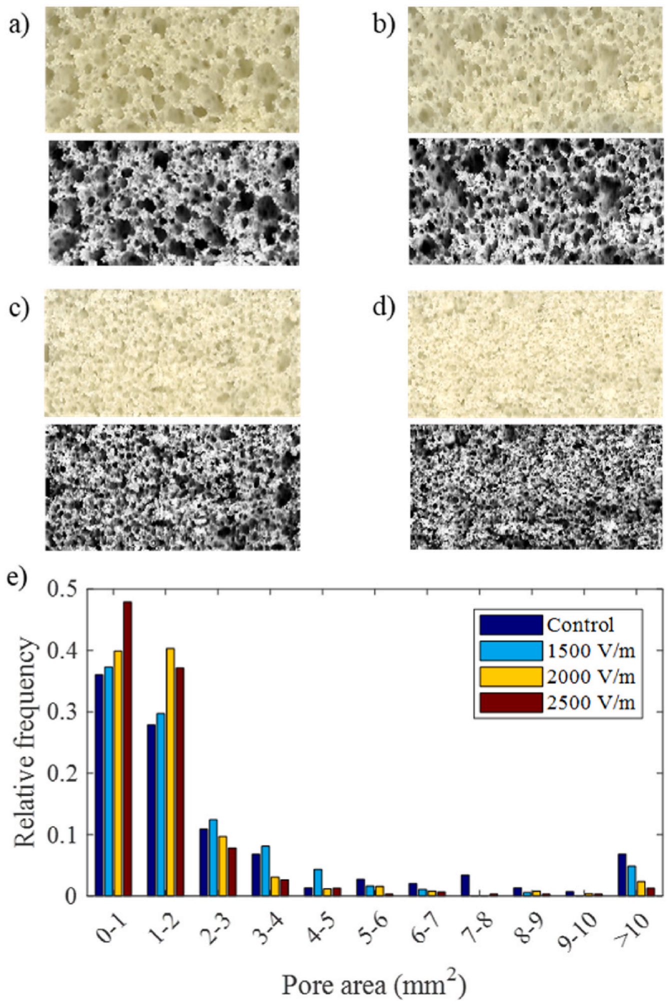

Fig. 4. Scanned cross section image of the samples used to porosity calculations (25 × 50 mm^2 area), and grayscale image after histogram equalization: a) Control; b) OH 1500 V/m; c) OH 2000 V/m; d) OH 2500 V/m e) relative distribution of pore area for different samples.

Table 4
Porosity calculated from image analysis[a].

	Porosity (number of pores/cm^2)	Average pore area, mm^2
CH	11.68	2.00 ± 1.91
OH 1500 V/m	14.70	1.82 ± 1.53
OH 2000 V/m	20.50	1.36 ± 0.81
OH 2500 V/m	24.40	1.26 ± 0.81

[a] Values expressed mean ± standard deviation (Weibull distribution).

4. Conclusions

In this work an ohmic cell was built to bake gluten free sponge cake, and performance of the system was compared with conventional hot air baking. Baking time was significantly reduced using the ohmic system, and reduction was larger as increasing electric field. Similarly, higher energy efficiencies and lower specific energy consumptions were reached with the ohmic system. Weight loss was lower for the ohmic system, and due to the volumetric nature of heating, lower crumb humidities were obtained; for conventional baking mostly the weight loss is at the crust. Between OH conditions, the slowest one (1500 V/m, with baking time more than 2 times the baking time at 2500 V/m) produced drier crumbs. Due to the lack of dehydrated surfaces and volumetric heating, ohmic baked samples experiences a larger volume expansion, which is a main concern for such kind of products. Other quality features were similar for both baking methods, although all the texture parameters are worse in the slowest OH condition, linked to its dried crumb.

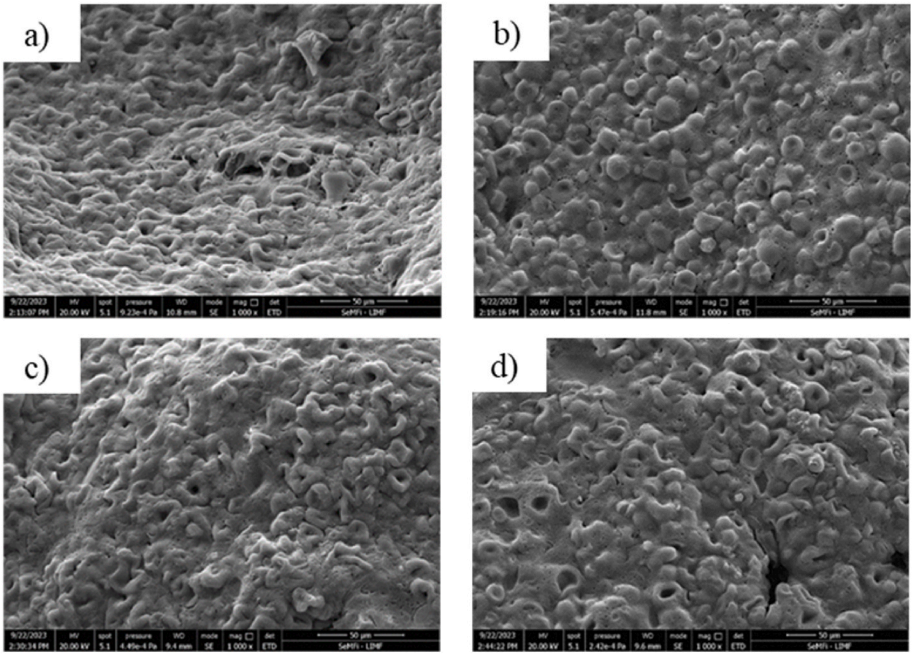

Fig. 5. Scanning electron microscopy (SEM) micrographs of crumbs at 1000x. a) CH; b) OH 1500 V/m; c) OH 2000 V/m; d) OH 2500 V/m.

Therefore, although OH appears as a promising baking technology, with low baking times and high energy efficiencies, the control of crumb moisture still needs further research. For ohmic baked samples, the absence of a characteristic brown top surface color could be determinant for bread or bakery products without topping. This subject can be addressed using a later or simultaneous stage of radiative and/or hot air, it will be the next step of our research. In bakery products like sponge cakes a topping is usually employed, which overcome such disadvantage.

CRediT authorship contribution statement

N.G. Mattioli: Writing – original draft, Validation, Methodology, Investigation, Data curation. **D.F. Olivera:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **V.O. Salvadori:** Writing – review & editing, Resources, Project administration. **F. Marra:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **S.M. Goñi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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