



# A comparative evaluation of conventional, microwave and hybrid baking methods and their impact on bread quality, acrylamide formation and sustainability

Leyli Vahid Dastjerdi<sup>a</sup>, Valentina Stojceska<sup>a,\*</sup>, Maria Oruna-Concha<sup>b</sup>,  
Julia Rodriguez-Garcia<sup>b,c</sup>, Savvas Tassou<sup>a</sup>

<sup>a</sup> Brunel University London, College of Engineering Design and Physical Sciences, Centre for Sustainable Energy Use in Food Chains, Uxbridge, UB8 3PH, UK

<sup>b</sup> University of Reading, Department of Food & Nutritional Sciences, Whiteknights, Berkshire, Reading, RG6 6DZ, UK

<sup>c</sup> Nutrition and Food Science Area, Preventive Medicine and Public Health, Food Science, Toxicology and Forensic Medicine Department, Faculty of Pharmacy and Food Sciences, Universitat de València, Av. Vicent Andrés Estellés, s/n, Burjassot, València, 46100, Spain

## ARTICLE INFO

### Keywords:

Conventional oven  
Domestic microwave  
Industrial solid-state microwave  
Loaf volume  
Texture  
Acrylamide  
Sustainability

## ABSTRACT

This study investigated the effects of conventional baking (CB), domestic microwave (DM), industrial solid-state microwave (IM), and hybrid baking approaches on the physicochemical properties, acrylamide formation, energy consumption, and environmental impact of bread. The results revealed that across an eight-day storage period, moisture content decreased significantly in all samples; however, IM breads retained the highest moisture, resulting in the lowest hardness values and slower staling, while DM breads showed the greatest moisture loss and firmness. Crust colour varied significantly with heating mode with CB breads produced the darkest crust due to increased Maillard reactions while IM and DM breads exhibited lighter crusts because of lower surface temperatures. Specific volume was highest in CB breads, with microwave-only breads exhibiting reduced expansion due to rapid internal heating, though hybrid methods partially mitigated this effect. Crumb microstructure analysis showed that IM and DM breads developed larger and more irregular cells compared to CB breads, because of the distinct heating patterns and pressure gradients produced by microwave systems. Acrylamide concentrations were significantly lower in all microwave and hybrid treatments than in CB samples, because of reduced surface browning and shorter exposure to high-temperature, low-moisture conditions. Overall, industrial solid-state microwave baking demonstrated lower energy consumption and improved environmental sustainability while producing bread with reduced acrylamide formation and acceptable quality, highlighting its strong potential for sustainable industrial baking applications.

## 1. Introduction

Bread is one of the most widely consumed cereal-based foods worldwide, and its quality is influenced by formulation and processing conditions. Parameters such as crumb structure, texture, moisture distribution, and crust colour are critical attributes that determine consumer acceptance and overall product quality. Variations in ingredient composition, processing parameters, and baking technologies can significantly influence these physicochemical characteristics as well as the nutritional and technological properties of bread products. Previous studies have shown that modifications in formulation or processing conditions can affect bread structure, texture, and shelf-life stability

(Arslanhan and Karaođlan, 2025; Kaur et al., 2025).

When considering different baking technologies, the conventional baking remains dominant method that relies on hot air heat transfer through conduction, convection and radiation within an oven cavity. This is an essential process where heat gradually penetrates the dough to drive main transformations like starch gelatinisation, protein denaturation, gas expansion and crust formation, which collectively determine the structural and sensory attributes of the final product. However, the conventional ovens are energy-intensive, often exhibit low heat transfer efficiency and may generate longitudinal temperature variations, potentially leading to inconsistent texture, colour and moisture distribution (Chhanwal et al., 2012). As energy costs rise and emphasis on

\* Corresponding author.

E-mail address: [Valentina.Stojceska@brunel.ac.uk](mailto:Valentina.Stojceska@brunel.ac.uk) (V. Stojceska).

<https://doi.org/10.1016/j.jfoodeng.2026.113210>

Received 9 December 2025; Received in revised form 3 June 2026; Accepted 9 June 2026

Available online 12 June 2026

0260-8774/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

sustainability becomes a priority, optimising conventional processes and exploring alternative baking technologies has become increasingly important. As a result, a range of innovative baking technologies such as infrared, vacuum, ohmic and microwave baking have been investigated as potential alternatives to conventional baking. Infrared baking (near- and far-infrared) provides rapid surface heating and can reduce baking time and energy consumption but may modify crust formation and texture (Rastogi, 2012). Vacuum baking operates at a reduced pressure, shortens baking time, prevents oxidative reactions and improves the microstructure of baked products (Devu et al., 2022). It also been shown that minimising the formation of harmful compounds such as acrylamide and hydroxymethylfurfural, reduces sugar degradation and inhibits the formation of Maillard reaction intermediates, thereby limiting heat-induced chemical changes and improving food safety (Yildiz et al., 2017; Cappelli et al., 2021). Ohmic heating uses electrical conductivity within the dough to generate internal heat, with factors such as temperature, salt content and porosity influencing heat distribution and offering opportunities for process optimisation (Gally et al., 2016). Microwave baking is another promising approach due to its rapid volumetric heating, which offers significantly shorter processing times and improved energy efficiency. However, uneven distribution of electromagnetic fields often leads to hot and cold spots, limiting starch gelatinisation, reducing volume expansion and negatively affecting crumb structure, moisture retention and sensory properties (İçöz et al., 2004; Ozkoc et al., 2009(a); Bou-Orm et al., 2021). These limitations have restricted industrial application (Chandrasekaran et al., 2013; Vadivambal and Jayas, 2010). To address these challenges, industrial solid-state microwave ovens, which use semiconductor-based generators rather than magnetrons, have emerged as an advanced alternative. These systems employ semiconductor-based generators, enabling precise frequency control, improved field uniformity and heating consistency, leading to improved product quality and reduced energy consumption (Atuonwu and Tassou, 2018). Despite their considerable potential to improve sustainability and reduce carbon emissions, their application in breadmaking industry has not yet been systematically investigated. To overcome the limitations of conventional and multiple baking methods, hybrid baking systems combining two or more baking methods have been developed. These approaches aim to improve heat transfer, shorten baking time, improve product quality and increase energy efficiency (Datta and Rakesh, 2013). Previous studies have demonstrated several benefits. For instance, Keskin et al. (2004) reported that halogen lamp–microwave hybrid baking improved specific volume and colour compared with conventional baking, although increased firmness and moisture loss were also observed (Chhanwal and Anandharamakrishnan, 2014). showed that infrared–conventional hybrid baking increased loaf volume, improved moisture retention and improved sensory quality while reducing firmness. Similarly, Panirani et al. (2023) found that infrared–conventional combinations produced the highest volume expansion and most desirable texture, while ohmic–conventional methods resulted in lower expansion due to rapid early drying and impaired gas retention. Given the central role of heating mode in determining bread quality, there is a clear need for innovative baking technologies that can accelerate processing, improve product quality and reduce environmental impact. To date, research on industrial solid-state microwave technology in food processing remains very limited, particularly in the field of bread baking. Moreover, no previous studies have comprehensively evaluated the baking performance of industrial solid-state microwave systems or hybrid use of solid-state microwave–conventional baking methods in comparison with conventional ovens and domestic microwave systems in terms of bread quality, physicochemical characteristics, acrylamide formation, energy efficiency and sustainability. Therefore, the potential of these emerging technologies for bread production and commercial application remains insufficiently understood. Therefore, this study investigates the physicochemical properties of bread baked using an industrial solid-state microwave oven and compares them with breads baked in a

domestic microwave and a conventional oven. It further evaluates hybrid baking systems that combine conventional baking with both industrial solid-state and domestic microwave technologies. The study also considers the energy efficiency, economic implications and sustainability potential of these approaches. The main hypothesis of this research is that industrial solid-state microwave baking, alone or in combination with conventional baking will improve heating uniformity and bread quality and reduce processing energy compared with traditional baking methods.

## 2. Materials and methods

### 2.1. Dough and bread preparation

The ingredients used for bread making were: wheat flour (Shipton mill, United Kingdom; composition (w/w) of 11% protein, 1.2% fat, 0.5% sugar, 79% starch and 3.3% fibre), vegetable oil (6.52% of saturated fat, 31.95% of monosaturated fat and 61.53% of polyunsaturated fat, local supermarket, UK), dry yeast (Allinson, United Kingdom), lukewarm tap water, salt (NaCl) and sucrose local supermarket, UK).

The following formulation of breads was used: 1000 g flour, 40 g vegetable oil, 23 g salt, 30 g dry yeast, 60 g sugar and 600 mL water. Dry ingredients were mixed with water in a food processor (Acuma Stand Mixer, United Kingdom) using a S-shaped hook geometry at 100 rpm for 1 min; then the dough was mixed at 200 rpm for another 1 min. The mixing conditions were selected based on preliminary trials and applied consistently across all treatments to ensure experimental comparability. Although dough development was not formally assessed using a gluten window test, the dough exhibited acceptable handling and shaping characteristics during processing.

The resulting dough was divided into 9 pieces (350 g per piece), shaped and placed on greased trays for a single proofing step in a steam oven (Eco Catering Equipment, Rational SCC61E, 5 Senses, United Kingdom) at 30°C and 85% relative humidity for 55 min (Stojceska and Ainsworth, 2008). Three different baking processes were used individually and in combinations: convection oven (Eco catering equipment, Rational SCC61E, 5 Senses, United Kingdom), domestic microwave (Panasonic NN-CD87KSBPQ combination microwave oven, Japan) and industrial solid-state microwave (Industrial microwave system, United Kingdom). Overall, 21 samples (7 baking methods x 3 replicates) were prepared, as follows:

1. Conventional oven at 200°C for 20 min (CB). Those samples were used as reference samples.
2. Domestic microwave oven at a medium-high power setting (approximately 600–800 W) and a frequency of 2450 MHz for 5 min (DM).
3. Industrial solid-state microwave with similar conditions as DM samples, at 706 W and frequency of 2450 MHz for 5 min (IM).
4. Hybrid approach of DM for 5 min + CB for 5 min (DMCB<sub>1</sub>)
5. Hybrid approach of DM for 5 min + CD for 10 min (DMCB<sub>2</sub>)
6. Hybrid approach of IM for 5 min + CB for 5 min (IMCB<sub>1</sub>).
7. Hybrid approach of IM for 5 min + CB for 10 min (IMCB<sub>2</sub>)

After cooling, loaves were characterized and then packed in polymeric bags (PET + COEX EVOH/PE) and stored at ambient temperature for 1, 5 and 8 days.

DM baking was included as a reference condition to represent conventional fixed-frequency microwave heating, allowing comparison with the IM baking, which provides more precise power modulation and improved control of electromagnetic field distribution.

### 2.2. Analyses of the baked breads

#### 2.2.1. Moisture content

The moisture content of the bread crumb was determined at Days 1,

5 and 8 using a thermogravimetric moisture analyser Ohaus (Ohaus, BM 25, the United States). Approximately, 3 g of breadcrumbs were heated at 120 °C for 9 min until a constant mass was achieved. These conditions were selected based on preliminary trials to ensure complete moisture removal without sample scorching and are consistent with rapid thermogravimetric moisture determination methods previously applied for bakery products (Ohaus Corporation, 2018).

### 2.2.2. Colour measurement

The colour of crust of the breads was measured using a colorimeter (Chromameter CR-400, Konica Minolta, 2007). The results were expressed in accordance with the CIELAB system (illuminant C and 10° viewing angle). The parameters measured were L [indicates lightness and ranges from 0 (for black) to 100 (for white)], a [ranges from -a (for greenness) to +a (for redness)], and b [ranges from -b (for blueness) to +b (for yellowness)] (Konak et al., 2017; Wu and Sun, 2013). The colorimeter was standardised with a white plate, and the colour of the crust was measured at the centre point of the bread top.

In addition to the individual colour coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ), the total colour difference ( $\Delta E$ ) was calculated to evaluate the overall variation in crust colour among the different baking treatments. The  $\Delta E$  value represents the global colour difference between samples and was calculated according to Equation (1):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (1)$$

where  $L^*$ ,  $a^*$ , and  $b^*$  are the colour parameters of the analysed sample and  $L_0^*$ ,  $a_0^*$ , and  $b_0^*$  correspond to the colour values of the reference sample (conventionally baked bread).  $\Delta E$  values greater than approximately 3 are generally considered visually perceptible to the human eye (Pathare et al., 2013).

### 2.2.3. Texture analysis

Bread samples were cut into 20 mm thick slices using a slicer (Buffalo meat slicer 220 mm, United Kingdom). A single compression test was performed in the centre of a slice using a 20 mm diameter cylinder and 5 kg load cell (Texture Analyzer A-XT2, Plus-Upgrade, Stable Micro Systems, Godalming, UK). The test parameters include: test speed of 1 mm/s and at a constant speed of 2.0 mm/s for pre-test and post-test, a trigger force of 5.0 g and a compression distance of 40% of the slice thickness. From the force-time curves, the parameters of hardness (maximum peak force during the first compression cycle), was provided by the software Exponent (version 6.1.18.0, Stable Micro Systems, UK).

### 2.2.4. Volume of the bread

Volume, specific volume, length and weight of breads were measured using a Stable Micro Systems Volscan Profiler (Volscan profiler, Stable Micro Systems, England) at a set laser distance of 0.5 mm. The specific volume (ml/g) of the breads was calculated by dividing volume (ml) of the breads with weight (g).

### 2.2.5. Cellular structure of the bread crumb

The cell crumb structure of breads was determined according to Lau et al. (2022) methodology with minor modifications. A flatbed scanner (HP Scanjet G2710, Hewlett-Packard, United States) was used to scan the picture of the bread slice. The picture was then analysed using the Image J software (National Institute of Health, USA). The image was cropped from the centre of the slice to form a 5 cm × 4.5 cm crumb image, and then split into colour channel, and blue was selected. The image was binarized; the number of cells and the average cell size (in mm<sup>2</sup>) were calculated.

### 2.2.6. Acrylamide analysis

Acrylamide standards (acrylamide and 1,2,3-13 C-acrylamide) were obtained from Sigma-Aldrich®, USA. Solvents (HPLC water, methanol,

and LC-MS water containing 0.1% formic acid) were obtained from Fisher Scientific, UK. Bread samples were freeze-dried using laboratory freeze dryer (CHRIST Beta 1-8 LS Plus, scientific, United Kingdom), grounded using blender (Kenwood 3 in 1 blender, United Kingdom) and 0.1 ± 0.005 g samples were extracted with 3.8 mL deionised water and 0.2 mL of internal standard (1,2,3-13 C-acrylamide (1000 ppm in methanol) using 15-mL Falcon tubes. The samples were then shaken for 20 min using a mechanical shaker (Cole-Parmer vortex mixer, United Kingdom) at maximum setting (1800 rpm) followed by centrifugation at 9000 rpm for 10 min at 15 °C using a Sorvall™ ST 8 Small Benchtop Centrifuge (Thermo Scientific, United Kingdom). This centrifugation process resulted with the formation of a discrete fat layer on the sample's surface. Subsequently, 2 ml of the aqueous layer were extracted and filtered through a 0.2 µm syringe filter into a 2-mL vial for analysis. The samples were analysed using an Agilent 1260 Infinity and 6410 Triple Quad LC/MS with electrospray ion source (ESI) in positive mode, on a Hypercarb column (100 × 3.0 mm i.d., 5 µm film thickness) with a Hypercarb precolumn (10 × 3.0 mm i.d., 5 µm). The mobile phase was 0.1% aqueous formic acid at a flow rate of 0.3 mL/min at 30°C. The injection volume was 5 µL. The ESI source parameters were as follows: gas temperature 350°C, gas flow 10 L/min, nebuliser pressure 35 psi, capillary 3000 V and fragmentor voltage 40 V. The MRM transitions measured for acrylamide were m/z 75 → 55 (N<sub>2</sub> collision energy, 8 eV). An external calibration curve for acrylamide was prepared (0 ppb, 1 ppb, 2.5 ppb, 5 ppb, 10 ppb, 25 ppb, 50 ppb, 100 ppb, 250 ppb, and 500 ppb) to allow for quantification. The LC/MS method used for acrylamide analysis in this study had a limit of detection (LOD) of 1 µg/kg and a limit of quantification (LOQ) of 3 µg/kg (Halford et al., 2012).

### 2.2.7. Energy consumption, greenhouse gas emissions and overall cost

The electrical energy data for the conventional oven and microwaves were recorded at 10 s intervals using a Fluke 345 energy logger (Washington, USA). As conventional oven and industrial solid-state microwave were powered by three-phase power supply, the logger monitored the voltage of each phase and independently measured the respective line currents using induction current measuring principles. Similarly, for the domestic microwave, which operates on a single-phase power supply, the logger recorded the phase voltage, current, power factor, power and cumulative energy at 10 s intervals using a Fluke 345 energy logger (Washington, USA). Preheating energy was not included in the calculations, as industrial baking systems commonly operate under continuous production conditions with preheated ovens. Energy consumption of the microwave and conventional oven baking was calculated using Equation (2):

$$E_t = P * t \quad (2)$$

where  $E_t$  represents total energy consumption for baking (kW h),  $P$  output power (kW) and  $t$  baking time (h).

The electrical cost of baking, are calculated using Equation (3):

$$\text{Energy cost for baking} = E_t * \text{Unit rate} \quad (3)$$

where  $E_t$  represents total energy consumption for baking and is measured in kilowatt-hours (kWh) while unit rate for electrical consumption  $E_t$  is £0.34 per kilowatt-hour (kWh) assuming a fixed price from (Department for Energy Security and Net[LV1.1] Zero, 2026). (Since the experiments were conducted in 2022, a fixed electricity price of £0.34/kWh based on the average UK tariff during that period was used for comparative purposes only).

The carbon footprint was calculated by multiplying the energy consumption (kWh) with the electricity emission conversion factor as shown in Equation (4) (Carbon Trust, n.d). The emission factor for electricity consumption was taken from the Department of Environment, Food and Rural Affairs (DEFRA, 2022) corresponding to 0.191 kg CO<sub>2</sub>e per kWh. This factor includes contributions from CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions associated with electricity generation. According to DEFRA

(2022), the electricity emission factors correspond to 0.1933 kg CO<sub>2</sub>, 0.0008 kg CH<sub>4</sub> and 0.0013 kg N<sub>2</sub>O per kWh, resulting in a combined value of 0.191 kg CO<sub>2</sub>e per kWh.

$$\text{GHG emission} = E * X \quad (4)$$

where E represents total energy consumption for baking (kWh) and X emission factor (0.191).

### 2.2.8. Statistical analysis

All experimental data were conducted in triplicate, and results are reported as mean ± standard deviation. The data were analysed using one-way analysis of variance (ANOVA) with a 95% confidence level ( $P < 0.05$ ), and multiple comparisons were performed using Duncan's test in SPSS 22.0 software (SPSS, Chicago, Illinois, USA).

## 3. Results and discussion

Fig. 1 shows images of breads produced using conventional, domestic microwave, and industrial solid-state microwave baking modes, while Fig. 2 the corresponding differences in their heat transfer mechanisms. In conventional baking, heat transfer occurs through a combination of convection, conduction, and thermal radiation. Energy is transferred from the oven environment to the product surface and subsequently conducted toward the core, resulting in a temperature gradient from the crust to the crumb (Mondal and Datta, 2008; Chhanwal et al., 2012). In contrast, microwave baking is based on dielectric heating, where electromagnetic energy is absorbed volumetrically within the product through dipole rotation of polar molecules (primarily water) and ionic conduction (Vadivambal and Jayas, 2010; Chandrasekaran et al., 2013). In domestic microwave systems, which typically operate using magnetron-based fixed-frequency radiation (commonly 2.45 GHz), non-uniform electromagnetic field distribution leads to the formation of localised hot and cold spots, resulting in uneven heating patterns within the product (Sumnu, 2001; Chandrasekaran et al., 2013). The recent advances in industrial solid-state microwave systems demonstrated an improved field uniformity and controllable frequency, resulting in more homogeneous heating and improved process control compared to domestic microwave systems, while still maintaining the rapid heating characteristics of microwave processing. (Atuonwu and Tassou, 2018).

The characteristics of the baked breads using different heating mechanisms, including moisture content, colour, volume, hardness, cellular structure, acrylamide levels, as well as environmental and economic costs, are critically evaluated in this section.

### 3.1. Moisture content of breads

Fig. 3(a) presents the changes in moisture content of breads baked using seven different modes over an eight-day storage period. A significant decrease in moisture content ( $p < 0.05$ ) was observed in all breads during the storage period, which is consistent with typical staling behaviour. Among the samples, breads baked using IM showed significantly ( $p < 0.05$ ) highest moisture content on both day 1 and after 8 days of storage, with values of 29.6% and 25%, respectively. In contrast, breads baked using DM consistently showed the lowest moisture content, recording 15.6% on day 1 and 7.7% at 8 days of storage. Hybrid breads showed intermediate trends with IM based hybrids (IMCB<sub>1</sub> and IMCB<sub>2</sub>) maintaining significantly ( $p < 0.05$ ) higher moisture content compared to the DM hybrid (DMCB<sub>1</sub> and DMCB<sub>2</sub>). These differences can be attributed to the fundamental distinctions in heat transfer between the baking technologies. DM ovens operate by rapidly exciting water molecules, generating considerable internal vapour pressure and steep temperature gradients. This accelerates moisture migration toward the surface and intensifies evaporation, resulting in substantial water loss both during and after baking. Similar moisture-reducing effects of domestic microwave heating have been reported in previous studies, largely due to the rapid rate of internal heating and limited opportunity for moisture redistribution (Sumnu, 2001; Ozkoc et al., 2009b). By contrast, IM technology provides a more controlled and uniform electromagnetic field distribution, which reduces excessive steam generation and allows the bread matrix to retain moisture more effectively. This behaviour agrees with observations by Dinani et al. (2020), who demonstrated that solid-state microwave systems reduce heating non-uniformity and minimise surface dehydration. CB which operates through gradual heating by convection and conduction, allows more controlled evaporation but still results in significant moisture loss due to prolonged exposure to high temperatures. Hybrid methods incorporating IM retained more moisture than CB breads and considerably more than DM-based hybrids, indicating that the more uniform heating profile provided by IM contributes positively to moisture retention. The

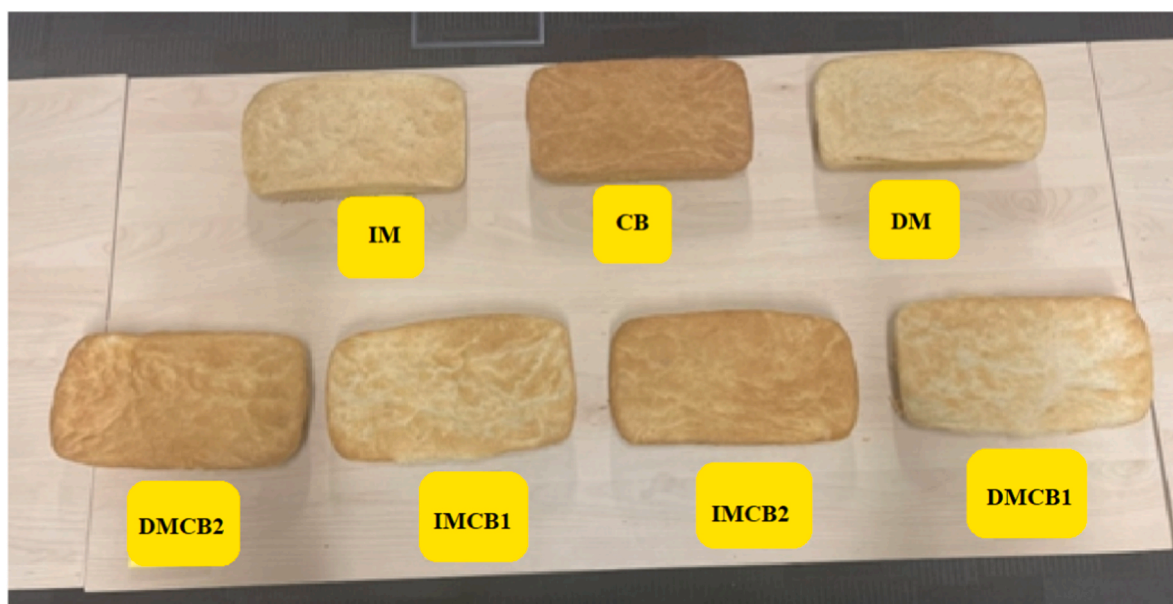


Fig. 1. The images of the baked breads with different baking modes (CB- conventional oven; DM - domestic microwave baking; IM-industrial solid-state microwave baking; DMCB - (DM + CB baking); IMCB - (IM + CB baking)).

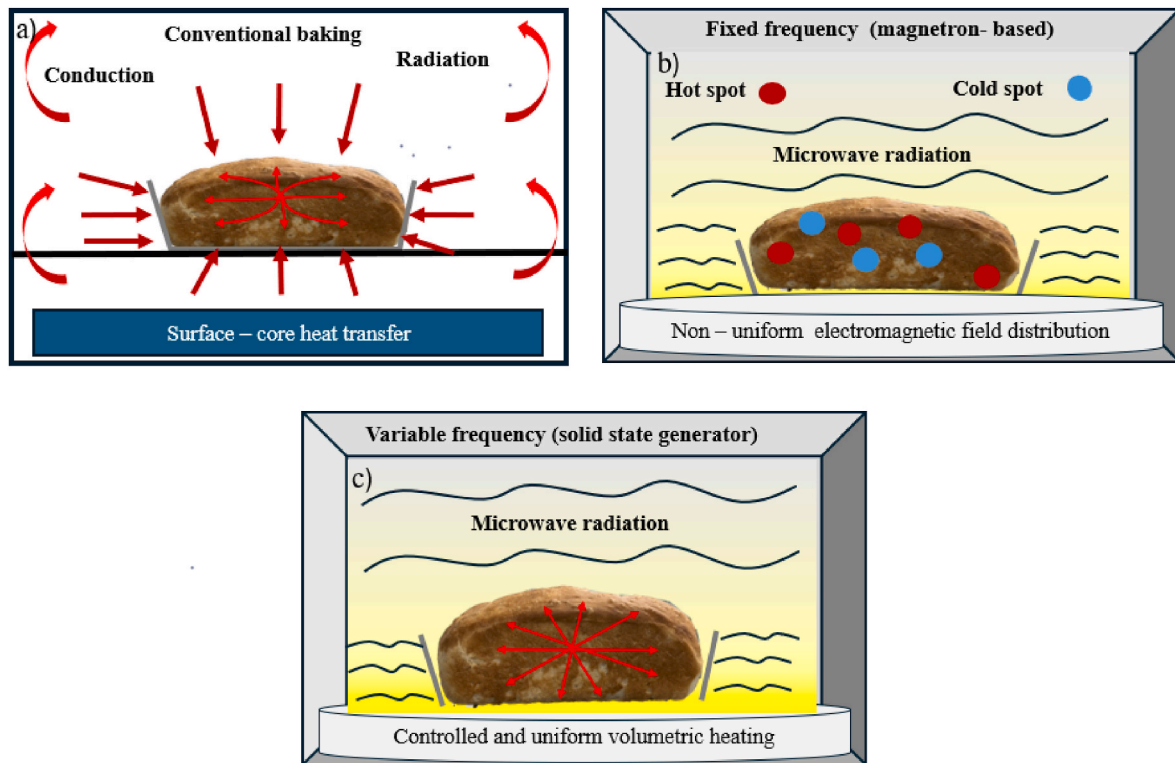


Fig. 2. Comparison of heat transfer mechanisms in (a) conventional, (b) domestic microwave and (c) industrial solid-state microwave baking modes.

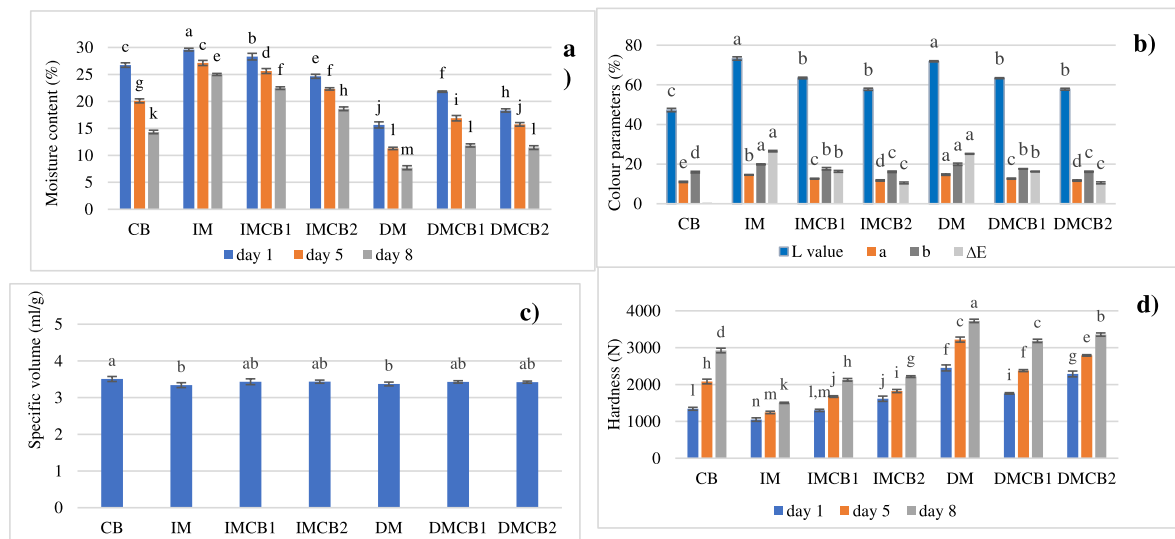


Fig. 3. a) Moisture content b) colour parameters c) specific loaf volume d) hardness of baked breads (CB- conventional oven; DM - domestic microwave baking; IM- industrial solid-state microwave baking; DMCB - (DM + CB baking); IMCB - (IM + CB baking)) \*Note: Lowercase letters indicated the significant difference ( $p < 0.05$ ) between different bread samples baked with different baking technologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

moisture content was strongly influenced by the intensity and distribution of heating within the bread, with microwave systems showing the greatest variance due to their fundamentally different mode of heat generation.

### 3.2. Colour of bread crust

Fig. 3(b) presents the variation in the colour changes across various baking methods, as represented by  $L^*$ ,  $a^*$ , and  $b^*$ . Breads baked using IM and DM displayed significantly ( $p < 0.05$ ) higher  $L^*$  value, indicating

lighter crust with no significant difference between the two baking modes. The breads baked using hybrid baking methods, IMCB<sub>1</sub>, IMCB<sub>2</sub>, DMCB<sub>1</sub>, and DMCB<sub>2</sub>, displayed significantly ( $p < 0.05$ ) lower  $L^*$  values than DM and IM but higher than CB baked breads. Although statistically significant differences in  $L^*$  values were observed between treatments, the magnitude of the variation was relatively small, suggesting that these differences may have limited practical relevance in terms of visual perception of crust colour. In terms of  $a^*$  and  $b^*$  values, the same trend was observed for the breads baked DM and IM showing significantly ( $p < 0.05$ ) higher values among other samples, whereas breads baked using

CB exhibited the lowest values. These results are consistent with those reported by İcöz et al. (2004), who observed that increasing baking time and temperature decreases  $L^*$  values and produces a darker crust. This occurs because browning reactions, including the Maillard reaction and caramelisation, intensify at higher surface temperatures and lead to the formation of melanoidin pigments responsible for darker crust colour (Dessev et al., 2020). The higher  $L^*$  values observed in both IM and DM's baked breads can therefore be attributed to the inability of the crust surface to reach the temperatures required for these browning reactions to proceed (Yolacaner et al., 2017). In hybrid baking, the conventional oven stage raises the surface temperature sufficiently to initiate Maillard reactions, resulting in a darker crust compared with IM- and DM-only breads, although hybrid breads remain lighter than conventionally baked breads due to the reduced exposure to high temperatures. Fig. 3 (b) also shows no significant differences ( $p > 0.05$ ) in  $a^*$  and  $b^*$  values among the hybrid-baked samples, indicating that while hybrid baking influences overall lightness, it does not substantially affect crust redness or yellowness. As a result, the calculated ( $\Delta E$ ) exhibited values well above the perceptibility threshold of ( $\Delta E > 3$ , confirming that colour differences were clearly visible. The largest deviations were observed for IM ( $\Delta E = 26.55$ ) and DM ( $\Delta E = 25.18$ ), indicating colours markedly different from CB, primarily due to increased lightness ( $L^*$ ) and reduced surface browning associated with limited Maillard reactions (İcöz et al., 2004). This is attributed to microwave volumetric heating, which reduces surface dehydration and alters browning kinetics. Hybrid treatments showed intermediate  $\Delta E^*$  values; IMCB<sub>1</sub> and DMCB<sub>1</sub> remained notably different from CB, while IMCB<sub>2</sub> and DMCB<sub>2</sub> were closest to CB due to the extended conventional baking phase, suggesting partial restoration of browning.

### 3.3. Bread's volume, specific volume and length

Fig. 3 (c) illustrates the impact of different baking methods on, specific volume of the breads. The average of the loaf volume ranged from 1166 ml to 1191, while loaf length varied between 219.5 mm and 222.1 mm across samples. The bread volume and loaf length did not differ significantly ( $p < 0.05$ ) among the samples, and they are not presented graphically, however, the specific volume which considers the ratio of loaf volume to loaf weight, showed significant ( $p < 0.05$ ) difference. The CB baked breads exhibited significantly ( $p < 0.05$ ) highest specific volume compared to all other samples; however, no significant differences were detected between CB and hybrid-baked breads. IM and DM baked breads demonstrated lower specific volume comparable to CB breads, with no statistical differences. The higher specific volume of CB breads can be attributed to the favourable thermal conditions that conventional ovens provide. Gradual external heat transfer allows the dough to reach temperatures conducive to proper gas expansion, starch gelatinisation, and gluten network development. This controlled heating promotes sufficient gas retention, yielding a lighter and more aerated crumb structure (Keskin et al., 2004; Sumnu et al., 2007). In contrast, breads baked solely with microwaves (IM or DM) lack adequate external heat exposure and often fail to achieve the sustained high crumb temperatures (around 200°C) required for full volume expansion. Rapid volumetric heating can prematurely denature gluten and accelerate water evaporation, weakening gas cell walls before full expansion takes place. This results in denser loaves with lower specific volumes, in accordance with earlier reports (Sumnu et al., 2007). Hybrid methods mitigate this limitation by integrating conventional heating, enabling more complete structural setting and improving specific volume relative to microwave-only breads.

### 3.4. Hardness of breads

Fig. 3(d) presents the hardness values of the breads over an eight-day storage period. IM breads consistently exhibited significantly ( $p < 0.05$ )

lowest hardness values while DM baked breads showed significantly ( $p < 0.05$ ) firmest across all storage days. This pattern closely paralleled the moisture content results, as confirmed by the strong negative correlations between moisture and hardness ( $R^2 = 0.98, 0.97, \text{ and } 0.98$  for days 1, 5, and 8). To indicate practical significance, hardness was expressed as a relative to CB. On day 1, IM and IMCB<sub>1</sub> were slightly softer ( $-21\%$  and  $-7\%$ ), whereas DM and DMCB<sub>2</sub> were markedly harder ( $+71\%$  and  $+64\%$ ), indicating clear textural deterioration. By day 5, IM remained softer ( $-35\%$ ) and DM harder ( $+60\%$ ), with hybrid treatments showing intermediate behaviour; IMCB<sub>1</sub> and IMCB<sub>2</sub> were slightly lower than CB ( $-15\%$  and  $-5\%$ ), while DMCB<sub>1</sub> and DMCB<sub>2</sub> were higher ( $+20\%$  and  $+35\%$ ). By day 8, IM breads maintained lower hardness ( $-48\%$ ), with IMCB<sub>1</sub> and IMCB<sub>2</sub> also remaining below CB ( $-28\%$  and  $-21\%$ ), whereas DM, DMCB<sub>1</sub>, and DMCB<sub>2</sub> exceeded CB by approximately 31%, 7%, and 17%, respectively. These results are consistent with the understanding that crumb firming during storage is closely linked to moisture loss and starch retrogradation. Dinani et al. (2020) reported that solid-state microwave systems deliver a more uniform electromagnetic field and minimise localised overheating compared with conventional magnetron-based microwaves. This improved heating uniformity likely contributed to the softer crumb observed in IM breads relative to CB and DM samples, as more homogeneous temperature distribution reduces excessive surface drying and prevents premature starch and protein denaturation. In contrast, the higher hardness of DM breads can be explained by the rapid and uneven heating characteristic of domestic microwaves, which accelerates moisture evaporation and intensifies staling (Bou-Orm et al., 2021). The data presented in Fig. 3(a) and (d) support this interpretation, showing that DM breads had the lowest moisture content and correspondingly the highest hardness values, indicating that moisture retention plays a dominant role in determining crumb firmness. This behaviour reflects the interaction between microwave heating and the molecular structure of bread. Rapid dielectric heating in DM systems can disrupt the gluten network by causing faster protein denaturation and excessive dehydration, which ultimately weakens the structural matrix and increases firmness (Boukid et al., 2018). Fig. 4 further confirms this relationship, revealing a strong negative correlation between moisture content and hardness over storage, with  $R^2$  values ranging from 0.96 to 0.98. This strong association aligns with the established understanding that moisture loss accelerates starch retrogradation, particularly amylose reassociation, which increases crumb rigidity during staling. Ozkoc et al. (2009a) similarly reported that microwave-baked breads exhibit higher hardness due to enhanced amylose leaching and the subsequent formation of hydrogen bonds between gelatinised starch and gluten proteins. This promotes rapid retrogradation and produces a firmer, drier crumb over time, consistent with the findings of Bou-Orm et al. (2021). Comparable results were reported by İcöz et al. (2004), who observed that breads baked in microwave-halogen systems hardened more rapidly than conventionally baked breads because the higher heating rate increased moisture loss and accelerated matrix setting. Hybrid baking methods that combined DM heating with a conventional oven stage (DMCB<sub>1</sub> and DMCB<sub>2</sub>) produced significantly lower hardness values than DM-only breads. This suggests that the conventional heating phase stabilises the gluten-starch network more gradually, reducing the excessive firmness typically associated with rapid microwave heating. This outcome agrees with Konak et al. (2017), who demonstrated that incorporating a conventional baking phase into microwave processing reduces total baking time while improving textural quality, resulting in softer and more desirable products.

### 3.5. Cell crumb structure of breads

Fig. 5 illustrates the crumb structures of breads produced using the different baking modes. Quantitative image analysis revealed that IM- and DM-baked breads contained a significantly higher ( $p < 0.05$ )

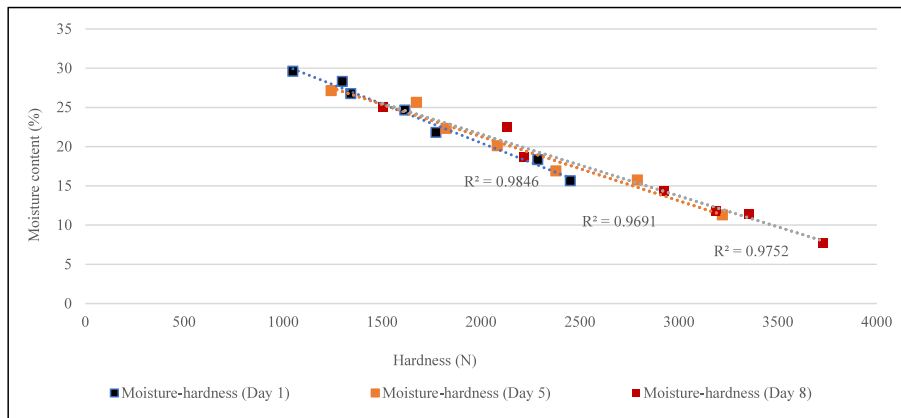


Fig. 4. Correlation between moisture content and hardness of the baked breads on days 1,5 and 8.

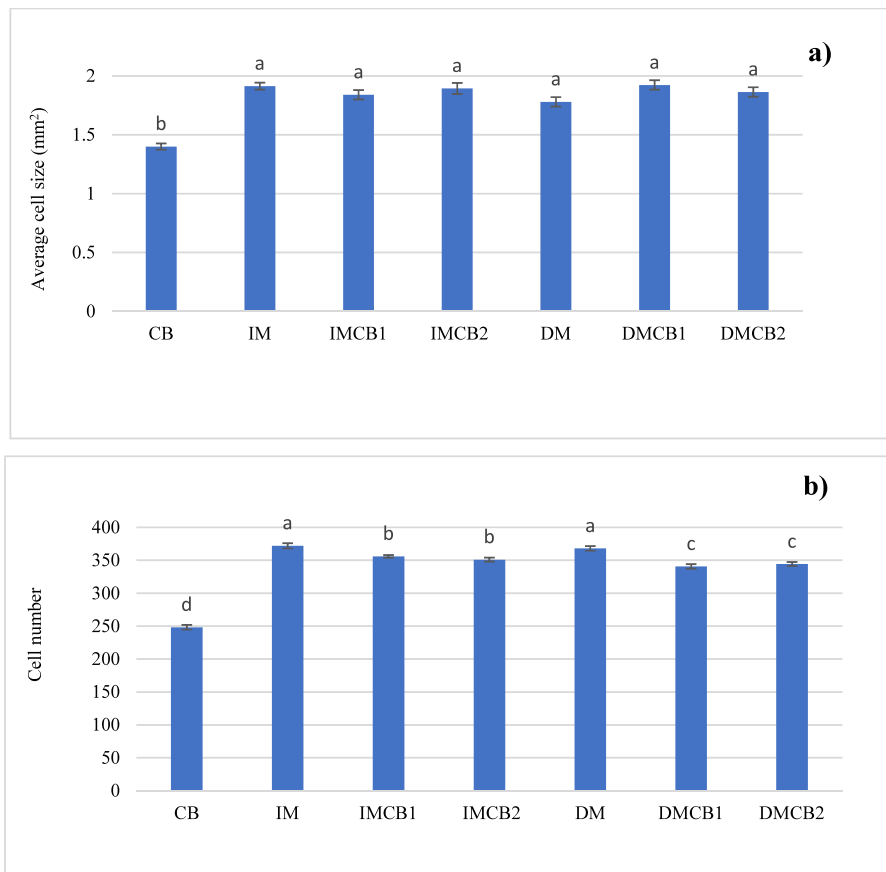


Fig. 5. The effect of different baking modes on the structure of the breads: a) average cell size, b) cell number of baked breads with different technologies (CB-conventional oven; DM - domestic microwave baking; IM-industrial solid-state microwave baking; DMCB - (DM + CB baking); IMCB - (IM + CB baking)) \*Note: Lowercase letters indicated the significant difference ( $p < 0.05$ ) between different bread samples baked with different baking technologies.

number of air cells compared with CB breads. No significant differences in cell count were observed between the hybrid methods DMCB<sub>1</sub> and DMCB<sub>2</sub>, or between IMCB<sub>1</sub> and IMCB<sub>2</sub>, indicating that the additional conventional heating step did not significantly amend cell numbers. In terms of cell dimensions, CB breads exhibited the smallest average pore size ( $p < 0.05$ ). Furthermore, visual inspection in Fig. 6 shows that CB produced a more uniform air cell distribution, whereas IM, DM, and hybrid samples displayed greater variability in pore size and distribution. These observations are consistent with Ozkoc et al. (2009a), who reported that conventional baking results in finer, more evenly distributed crumb cells due to the lower internal vapour pressure generated

during gradual heat transfer. In contrast, IM and DM breads in the present study displayed larger, irregularly shaped pores and a more heterogeneous crumb appearance. This agrees with earlier findings by Sumnu (2001), who noted that microwave heating, because of its rapid dielectric heating mechanism, induces accelerated water evaporation and rapid gas expansion, leading to irregular bubble growth and a coarser crumb texture. Similarly, Bou-Orm et al. (2021) reported that microwave-baked products typically exhibit non-uniform pore structures because the rapid heating rate disrupts the controlled setting of the gluten–starch matrix. Conventional ovens, by comparison, provide a slower and more uniform heat transfer via convection and conduction,

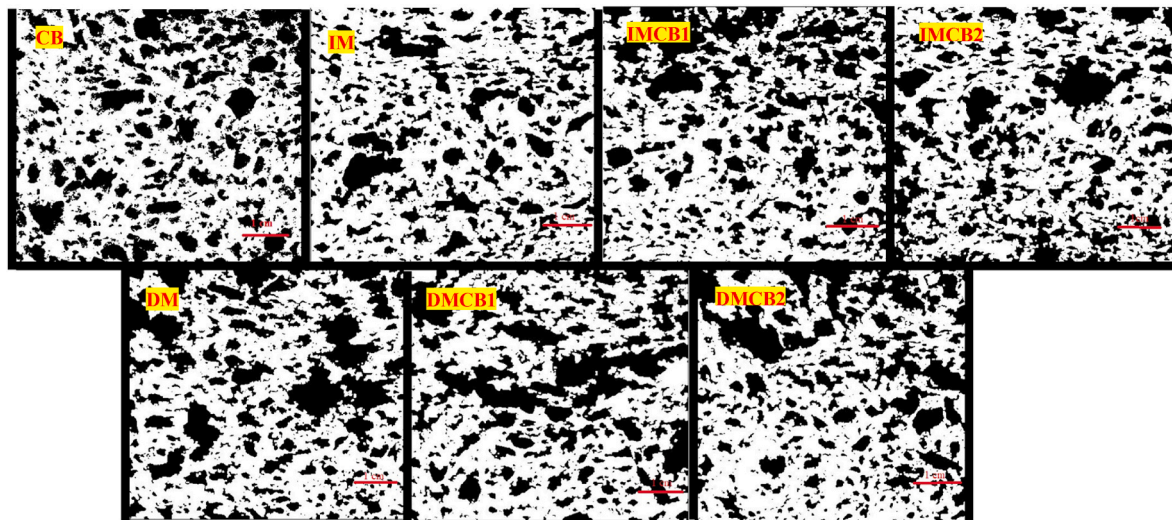


Fig. 6. Cellular structure of the bread crumb baked with different baking technologies (CB- conventional oven; DM - domestic microwave baking; IM-industrial solid-state microwave baking; DMCB - (DM + CB baking); IMCB - (IM + CB baking)) \*Note: Scale bars, 1 cm.

allowing gas cells to expand gradually and stabilise before crumb setting. This controlled process promotes the development of smaller, more uniform pores, as also noted by Baik et al. (2000).

Fig. 6 further demonstrates that IM, DM, and all hybrid-baked breads had significantly ( $p < 0.05$ ) larger pore sizes than CB breads. The larger pores likely arise from the high internal pressure generated during microwave heating. Because microwave energy directly excites polar water molecules, steam is produced rapidly throughout the dough rather than migrating from the surface inward. This rapid vapour generation, combined with the high moisture removal rate associated with microwave heating (Mills et al., 2003), causes sudden expansion of gas cells and premature setting of an unstable structure, resulting in a looser, more porous crumb. This combination of elevated internal pressure and accelerated dehydration explains the reduced uniformity and increased pore size observed in the microwave and hybrid baking treatments. In summary, these structural characteristics may influence consumer perception and product acceptability. Although IM baking offers certain advantages for bakery applications, potential effects on crumb structure should be considered when evaluating overall product quality and its suitability for commercial adoption.

### 3.6. Acrylamide formation

Fig. 7 presents the acrylamide concentrations measured in breads produced using the different baking technologies. Significant ( $p < 0.05$ ) differences were observed across baking modes, with acrylamide levels ranging from 1.28  $\mu\text{g}/\text{kg}$  in IM breads to 22.05  $\mu\text{g}/\text{kg}$  in CB samples. No significant differences were detected between IM and DM breads and between the hybrid treatments IMCB<sub>1</sub> and DMCB<sub>1</sub> or IMCB<sub>2</sub> and DMCB<sub>2</sub>, suggesting that acrylamide formation in hybrid baking was not influenced by the type of microwave used. In contrast, CB breads exhibited significantly ( $p < 0.05$ ) higher acrylamide levels than all microwave-based treatments, particularly under longer baking times. The higher acrylamide levels in CB breads are consistent with previous research indicating that acrylamide formation during conventional baking is primarily driven by the Maillard reaction at the bread surface, where temperatures are highest (Michalak et al., 2017). Since the Maillard reaction is temperature and time dependent, extended baking promotes greater acrylamide accumulation (Michalak et al., 2020). In microwave baking, heat is generated volumetrically through dielectric heating rather than through the ambient hot air of an oven. As a result, surface temperatures remain lower, and moisture often condenses on the crust, delaying crust formation and suppressing the high-temperature, low-moisture conditions required for acrylamide synthesis (Devu et al.,

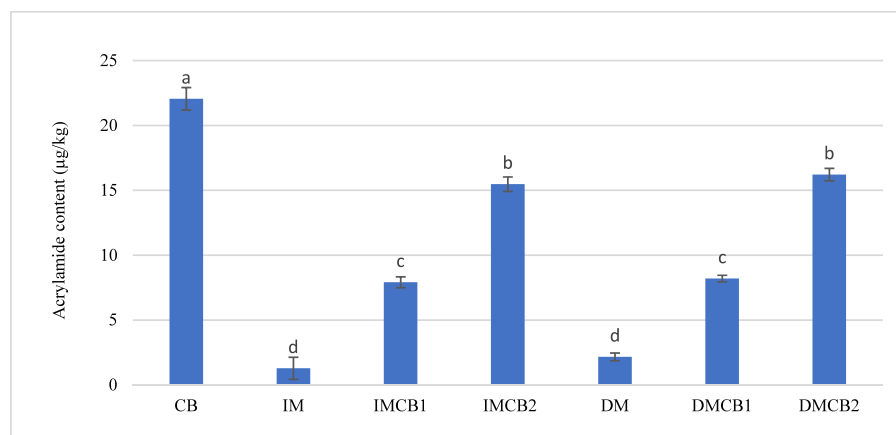


Fig. 7. Acrylamide content of baked breads with different baking modes (CB- conventional oven; DM - domestic microwave oven. IM-industrial solid-state microwave; DM-domestic microwave; DMCB - (DM + CB); IMCB - (IM + CB)) \*Note: Lowercase letters indicated the significant difference ( $p < 0.05$ ) between different bread samples baked with different baking technologies.

2022; De Pilli and Alessandrino, 2020). These findings align with Al-Ansi et al. (2019), who reported that microwave-baked biscuits contained 10% less acrylamide than conventionally baked samples, attributing the reduction to shorter processing times and reduced surface browning. However, the literature presents mixed results. Some studies have shown that microwave baking can produce higher acrylamide levels under certain conditions. For example, Michalak et al. (2017) observed that microwave-baked croquettes reached acrylamide concentrations of 420 µg/kg substantially higher than conventionally baked counterparts. This discrepancy may arise because microwaves heat foods internally, allowing temperatures within low-conductivity regions to rise rapidly. Such internal hotspots can trigger acrylamide formation even when surface temperatures remain relatively low (Yuan et al., 2007; Michalak et al., 2020). Taken together, these findings indicate that acrylamide formation in microwave baking is influenced by several interacting factors, including water activity, food matrix composition, microwave power, and exposure time. Despite the variability reported in previous studies, the present results demonstrate that both industrial solid-state microwaves and domestic microwaves produced lower acrylamide concentrations than conventional baking. This is likely due to reduced surface temperatures and shorter exposure to high-temperature conditions, both of which limit the progression of the Maillard reaction. Since the acrylamide concentrations detected in IM (1.28 µg/kg) and DM (2.82 µg/kg) baked breads were above LOD (1 µg/kg) but below the LOQ (3 µg/kg), acrylamide could be detected but not reliably quantified at these low concentrations. Therefore, these values should be interpreted with caution. Nevertheless, the results still indicate a substantially lower tendency for acrylamide formation in both microwave-baked breads compared with conventionally baked bread. From a regulatory perspective, acrylamide formation in cereal-based foods is addressed through mitigation measures established in Commission Regulation (EU) 2017/2158, which sets benchmark levels for different food categories. For soft bread, the benchmark level is 50 µg/kg (European Commission (2017)). The acrylamide concentrations measured in the present study ranged from 0.89 to 23.77 µg/kg, which are substantially below this benchmark value. These findings indicate that all baking technologies evaluated, produced bread with relatively low acrylamide levels. Nevertheless, conventional baking resulted in higher acrylamide concentrations compared with microwave-based treatments, which can be attributed to the higher surface temperatures and more intensive Maillard reactions occurring during conventional crust formation. In addition, acrylamide mitigation in cereal-based foods is also addressed through industry guidance and processing strategies that are part of quality assurance and process control frameworks. For example, the Acrylamide Toolbox, developed by FoodDrinkEurope. Acrylamide Toolbox (2019) in collaboration with industry and regulatory bodies, provides practical mitigation measures including formulation adjustments, processing controls, and targeted intervention steps for thermal food production such as bread (e.g., optimized time-temperature profiles, ingredient modification). Recent comprehensive reviews further summarise mitigation strategies in cereal products, including enzymatic treatments, additives, and baking process optimisation, indicating that a combination of technological and procedural controls can reduce acrylamide formation while balancing product quality (Cankaya et al., 2025). These frameworks support broader food safety and quality assurance efforts beyond the fundamental chemistry discussed earlier.

### 3.7. Evaluation of energy consumption, environmental and economic impact

Table 1 summarises the total energy consumption, environmental impact, and economic efficiency of bread baked using different heating modes. The results show that breads baked in a conventional oven required the highest energy input, whereas those baked using domestic microwave, industrial microwave, and hybrid systems used considerably less energy. Among all samples, industrial solid-state microwave

**Table 1**

Energy consumption, cost and carbon emission of different baking technologies (CB- conventional oven; DM - domestic microwave oven. IM-industrial solid-state microwave; DM-domestic microwave; DMCB - DM + CB); IMCB - (IM + CB)).

Samples	Energy consumption (kWh)	Total cost (£)	GHG emission (Kg of CO <sub>2</sub> )
CB	0.453 <sup>a</sup>	0.1532 <sup>a</sup>	0.086 <sup>a</sup>
IM	0.035 <sup>g</sup>	0.0054 <sup>g</sup>	0.006 <sup>g</sup>
IMCB <sub>1</sub>	0.118 <sup>f</sup>	0.0401 <sup>f</sup>	0.022 <sup>f</sup>
IMCB <sub>2</sub>	0.148 <sup>e</sup>	0.0503 <sup>e</sup>	0.028 <sup>e</sup>
DM	0.261 <sup>c</sup>	0.0887 <sup>c</sup>	0.049 <sup>c</sup>
DMCB <sub>1</sub>	0.231 <sup>d</sup>	0.0785 <sup>d</sup>	0.044 <sup>d</sup>
DMCB <sub>2</sub>	0.344 <sup>b</sup>	0.1169 <sup>b</sup>	0.065 <sup>b</sup>

\*Note: Lowercase letters in the same column indicated the significant difference ( $p < 0.05$ ) between different bread samples baked with different baking modes.

baking exhibited the lowest energy consumption. The hybrid baking process also required less energy than conventional baking, mainly because of its shorter processing time.

In conventional ovens, the oven walls and cavity must first be heated before heat is transferred to the product, resulting in higher overall energy demand. In contrast, microwave heating generates heat internally within the food through energy absorption, allowing direct volumetric heating and reducing energy losses associated with heating surrounding structures. This makes microwave processing more efficient than traditional baking methods (Bermúdez et al., 2015). Heat generation in microwave ovens occur through interactions between electromagnetic radiation and charged or polar molecules in the food, improving internal heat transfer and minimising the influence from the external environment (De Pilli and Alessandrino, 2020). Atuonwu and Tassou (2018) also reported that microwaves can significantly improve energy efficiency during food drying when power levels are matched to the moisture content and dielectric properties of the products, reducing energy reflections. They further demonstrated that industrial solid-state microwave systems outperform domestic microwave units due to their higher absorption efficiency. In terms of processing costs, IM baking proved to be the most economical option, with a cost of only £0.0054 per unit. This was followed by domestic microwave baking at £0.0887 per unit. The substantial cost reduction associated with IM baking highlights its potential as a sustainable and cost-effective solution for large-scale applications, offering clear advantages over conventional baking. Environmental impact assessments similarly show that industrial solid-state microwave baking produces the lowest greenhouse gas emissions (GHG) compared with conventional and domestic microwave baking. The reduced energy demand directly contributes to lower emissions, as less electricity is required to power the process. Although hybrid baking is not as energy efficient as IM baking, it still consumes less energy than CB due to shorter baking times, leading to reduced production costs and environmental impact. Integrating microwave technology, particularly industrial solid-state microwave into baking processes can significantly improve energy efficiency, lower operational costs, and improve sustainability by reducing carbon emissions and dependence on energy-intensive conventional methods. The energy consumption and greenhouse gas emission calculations presented in this study are based solely on the operational energy required during the baking process. Consequently, the results represent a process-level comparison of baking technologies rather than a full life-cycle environmental assessment, as factors such as equipment manufacturing, maintenance requirements, system lifespan, and scale-dependent efficiencies were not included.

It should be acknowledged that this study primarily relied on instrumental measurements of bread quality, including texture, moisture, colour, and structural characteristics. Although these parameters provide objective indicators of product properties and processing performance, sensory evaluation and consumer acceptability testing would



- varieties: effects of storage and relationship with acrylamide formation. *J. Agric. Food Chem.* 60, 12044–12055. <https://doi.org/10.1021/jf303756u>.
- İçöz, D., Sumnu, G., Sahin, S., 2004. Color and texture development during microwave and conventional baking of breads. *Int. J. Food Prop.* 7 (2), 201–213. <https://doi.org/10.1081/JFP-120022111>.
- Kaur, H., Kaur, K., Kaur, J., Meeta, N., Rehal, J., 2025. Enrichment of breads with fenugreek seeds for improved nutritional, functional, and storage stability. *Qual. Assur. Saf. Crop Foods* 17 (4). <https://doi.org/10.15586/qas.v17i4.1579>.
- Keskin, S.O., Sumnu, G., Sahin, S., 2004. Bread baking in halogen lamp–microwave combination oven. *Food Res. Int.* 37 (5), 489–495. <https://doi.org/10.1016/j.foodres.2003.12.007>.
- Konak, Ü., Certel, M., Karakas Budak, B., 2017. Effects of ultraviolet irradiation of batter and different baking methods on cake quality. *J. Microbiol. Biotechnol. Food Sci.* 7 (2), 113–117. <https://doi.org/10.15414/jmbfs.2017.7.2.113-117>.
- Konica Minolta, 2007. *Precise Colour Communication [LV1.1]: Color Control from Perception to Instrumentation*. Konica Minolta Sensing, Inc., Osaka, Japan.
- Lau, T., Clayton, T., Harbourne, N., Rodriguez-Garcia, J., Oruna-Concha, M.J., 2022. Sweet corn cob as a functional ingredient in bakery products. *Food Chem. X* 13, 100180. <https://doi.org/10.1016/j.fochx.2021.100180>.
- Michalak, J., Czarnowska-Kujawska, M., Klepacka, J., Gujska, E., 2020. Effect of microwave heating on the acrylamide formation in foods. *Molecules* 25 (18), 4140. <https://doi.org/10.3390/molecules25184140>.
- Michalak, J., Gujska, E., Czarnowska-Kujawska, M., Nowak, F., 2017. Effect of different home-cooking methods on acrylamide formation in pre-prepared croquettes. *J. Food Compos. Anal.* 56, 134–139. <https://doi.org/10.1016/j.jfca.2016.12.017>.
- Mills, E., Wilde, P.J., Salt, L.J., Skeggs, P., 2003. Bubble formation and stabilization in bread dough. *Food Bioprod. Process.* 81 (3), 189–193. <https://doi.org/10.1205/096030803765208651>.
- Mondal, A., Datta, A.K., 2008. Bread baking – a review. *J. Food Eng.* 86 (4), 465–474. <https://doi.org/10.1016/j.jfoodeng.2007.11.014>.
- Ohaus Corporation, 2018. MB23/MB25 Moisture Analyzer Instruction Manual. Ohaus Corporation, Parsippany, NJ, USA.
- Ozkoc, S.O., Sumnu, G., Sahin, S., 2009b. The effects of gums on macro and micro-structure of breads baked in different ovens. *Food Hydrocoll.* 23 (8), 2182–2189. <https://doi.org/10.1016/j.foodhyd.2009.04.009>.
- Ozkoc, S.O., Sumnu, G., Sahin, S., Turabi, E., 2009a. Investigation of physicochemical properties of breads baked in microwave and infrared–microwave combination ovens during storage. *Eur. Food Res. Technol.* 228 (6), 883–893. <https://doi.org/10.1007/s00217-008-0995-8>.
- Panirani, P.N., Darvishi, H., Hosainpour, A., Behroozi-Khazaei, N., 2023. Comparative study of different bread baking methods: combined ohmic–infrared, ohmic–conventional, infrared–conventional, infrared, and conventional heating. *Innov. Food Sci. Emerg. Technol.* 86, 103349. <https://doi.org/10.1016/j.ifset.2023.103349>.
- Pathare, P.B., Opara, U.L., Al-Said, F.A., 2013. Colour measurement and analysis in fresh and processed foods: a review. *Food Bioprocess Technol.* 6, 36–60. <https://doi.org/10.1007/s11947-012-0867-9>.
- Rastogi, N.K., 2012. Recent trends and developments in infrared heating in food processing. *Crit. Rev. Food Sci. Nutr.* 52, 737–760. <https://doi.org/10.1080/10408398.2010.504903>.
- Stojceska, V., Ainsworth, P., 2008. The effect of different enzymes on the quality of high-fibre enriched brewer's spent grain breads. *Food Chem.* 110 (4), 865–872. <https://doi.org/10.1016/j.foodchem.2008.02.074>.
- Sumnu, G., 2001. A review on microwave baking of foods. *Int. J. Food Sci. Technol.* 36 (2), 117–127. <https://doi.org/10.1046/j.1365-2621.2001.00439.x>.
- Sumnu, G., Datta, A.K., Sahin, S., Keskin, S.O., Rakesh, V., 2007. Transport and related properties of breads baked using various heating modes. *J. Food Eng.* 78 (4), 1382–1387. <https://doi.org/10.1016/j.jfoodeng.2006.01.004>.
- Vadivambal, R., Jayas, D.S., 2010. Non-uniform temperature distribution during microwave heating of food materials—a review. *Food Bioprocess Technol.* 3, 161–171. <https://doi.org/10.1007/s11947-008-0136-z>.
- Wu, D., Sun, D.W., 2013. Colour measurements by computer vision for food quality control – a review. *Trends Food Sci. Technol.* 29, 5–20. <https://doi.org/10.1016/j.tifs.2012.08>.
- Yıldız, H.G., Palazoğlu, T.K., Miran, W., Kocadağlı, T., Gökmen, V., 2017. Evolution of surface temperature and its relationship with acrylamide formation during conventional and vacuum-combined baking of cookies. *J. Food Eng.* 197, 17–23. <https://doi.org/10.1016/j.jfoodeng.2016.10.005>.
- Yolacaner, E.T., Sumnu, G., Sahin, S., 2017. Microwave-assisted baking. In: *The Microwave Processing of Foods*, pp. 117–141. <https://doi.org/10.1016/B978-0-08-100528-6.00006-1>.
- Yuan, Y., Chen, F., Zhao, G., Liu, J., Zhang, H., Hu, X., 2007. A comparative study of acrylamide formation induced by microwave and conventional heating methods. *J. Food Sci.* 72 (4), C212–C216. <https://doi.org/10.1111/j.1750-3841.2007.00304.x>.