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An investigation of the use of the solid-state microwave technology as an energy-efficient method to improve heating uniformity and moisture retention during the baking process

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Abstract. This study investigates heating uniformity and moisture retention in bread baked using industrial microwave in combination with conventional oven. Twelve samples have been prepared and temperature and humidity were measured at multiple zones using thermocouples and fibre optic sensors. Additionally, hardness and shelf if of the products was observed during the eight days of period. This research also analyses the environmental and economic implications of these baking methods, offering valuable understandings into advancements in baking technologies that promote energy efficiency and sustainability to the baking industry. Results showed that the involvement of the industrial solid-state microwave in the baking processes have a potential to develop more uniform temperature changes and water retention trough minimized surface drying, internal temperature gradients, and overall moisture loss which reduced the hardness of the products and improved the shelf life. Furthermore, industrial solid-state microwave baking showed as the most energy-efficient and cost-effective method, with lower emissions compared to conventional and other microwave baking modes, making it a more sustainable alternative.

1 Introduction

Breadmaking is one of the oldest and most widely practiced food processing technologies, with origins dating back thousands of years. Despite innovations in ingredients and formulations, the core process remains reliant on conventional oven baking. Oven temperature is a critical factor, as it drives the physicochemical and biological changes necessary for converting dough into bread [1]. However, conventional baking often results in non-uniform heating, potentially compromising product quality and consistency. This has prompted interest in alternative baking technologies such as microwave baking that offer improved uniformity without compromising with the bread quality.
Rakesh et al. [2] analysed the heating rates and uniformity in a domestic microwave combined with forced air and found that this combination improves heating speed while maintaining its uniformity. Geedipalli et al. [3] studied heat transfer in a microwave–jet impingement oven and reported improvements in both heating uniformity and thermal efficiency while the cooking time was reduced. Domestic microwave baking has the potential to minimise the baking time [4] although some challenges such as non-uniform distribution of electromagnetic waves have been detected that affect the final product quality [5,6]. A promising alternative is an industrial solid-state microwave technology, which offers more volumetric and uniform heating which could improve final product quality [7]. These alternative methods offer significant advantages such as proper management of high temperatures that can reduce baking time, which may positively influence the nutritional composition and sensory qualities of the baked products. To date, no studies have explored the performance characteristics of the use of an industrial solid-state microwave baking and its advantages over conventional technologies in terms of heating uniformity and moisture changes. Therefore, this study aims to evaluate heating uniformity and moisture variation during baking using an industrial solid-state microwave and conventional oven, separately and in a hybrid approach and to assess the resulting hardness of the baked bread.

2 Experimental Details

2.1 Baking preparation

Four types of bread, each with three replicates, were baked using an industrial solid-state microwave (Industrial microwave system, United Kingdom) (IM), a conventional oven (Eco catering equipment, Rational SCC61E, 5 Senses, United Kingdom) (CB) and two hybrid methods: IM for 5 minutes followed by CB for 5 minutes (IMCB1), and IM for 5 minutes followed by CB for 10 minutes (IMCB2).

2.2 Texture analysis

Bread slices were tested for hardness at the centre using a 20 mm cylinder and 5 kg load cell on a Texture Analyzer A-XT2 Plus (Stable Micro Systems, UK). A double compression test was conducted at 1 mm/s test speed, 2 mm/s pre/post-test speed, with 40% compression; analysis was performed in triplicate at day 1,5 and 8 after baking.

2.3 Temperature measurement

Conventional oven temperature was measured using K-type thermocouples (0.2 mm, TC SA, France) with PicoLog software (v5.25.3, Picolog Technology, USA) over 20 minutes for CB and 5–10 minutes for hybrid modes. For IM, fibre optic sensors (Omega, UK) recorded temperatures at three aligned positions including top, centre and bottom, repeated three times for accuracy over a 5-minute baking period.

2.4 Humidity measurement

Humidity was measured using a fibre optic AM2315C sensor (Ec-electric, Iran) with 24 VDC/115–230 VAC supply, 0–100% volumetric range, display readout, and 4–20 mA output. Data were recorded using PicoLog software and repeated three times at aligned top, centre, and bottom positions.

2.5 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 industrial 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. 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). Energy consumption of the industrial microwave and conventional oven baking was calculated using Equation:

$$E_t = P * t \quad (1)$$

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 the Equation 2:

Energy cost for baking =

$$E_t * Unit\ Rate \quad (2)$$

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 Npower, 2022.

The Greenhouse Gas (GHG) emissions was calculated by multiplying the energy consumption (kWh) with the conversion factor as shown in equation (3).

$$GHG\ emission = E * X \quad (3)$$

Where E_t represents the total energy consumption for baking (kWh) and X the emission factor (0.191) using emission factors as kg co2 e =0.1912, kg CO2 =0.1933, kg CH4 =0.0008 and kg N2O=0.0013.

2.6 Statistical analysis

The data were subjected to a one-way analysis of variance (one-way ANOVA), 95 % confidence was obtained ($P < 0.05$) using Duncan's method in SPSS 22.0 software (SPSS 2.0, Chicago, Illinois, US).

3 Results and Discussion

3.1 Hardness

Figure 1 presents the hardness of breads baked using different methods. Among them, IM baked bread showed significantly ($p \leq 0.05$) lower hardness over 8 days of storage, while CB baked bread had the highest values which could be due to its uniform heating. Similar observation was reported by Dinani et al. (2020), who demonstrated that solid-state microwave technology provides more even heat distribution and reduces localized overheating, which likely contributes to the softer texture observed in IM breads. The hybrid baking methods ($IMCB_1$ and $IMCB_2$), which combine microwave and conventional heating, also showed significantly ($p \leq 0.05$) lower hardness than CB breads. This suggests that hybrid baking reduces overall baking time and helps produce bread with a softer, more desirable texture. Across all samples, hardness increased gradually over the 8-day storage period, with the slowest increase observed in IM bread.

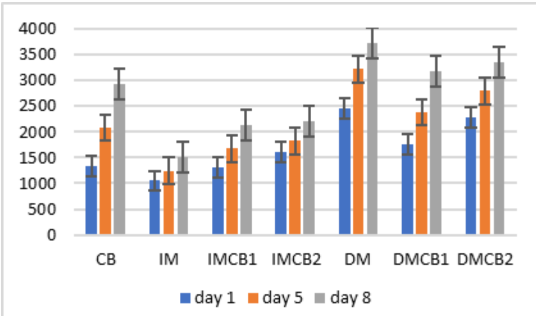
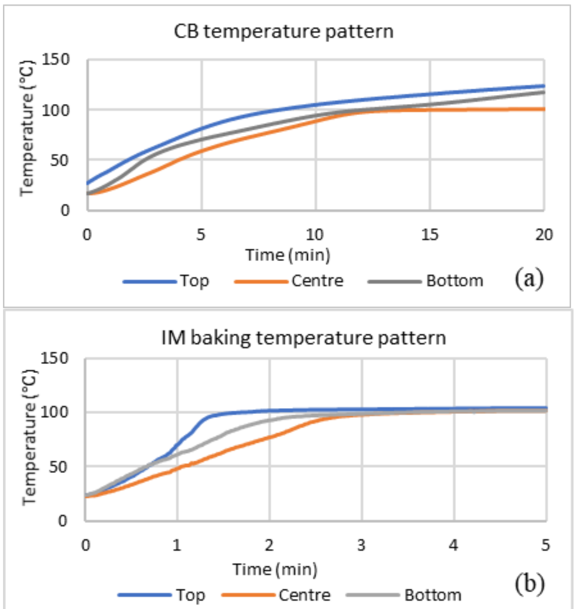


Fig. 1. Hardness of baked breads using different baking modes.

3.2 Temperature distribution

The temperature distribution of the baked breads is shown in Fig.2. It can be seen that in the IM breads, the temperature in all three different zones (top, centre and bottom) is closely aligned while in CB baked breads, the temperature in centre is significantly different from those top and bottom showing more temperature variation and less uniformity in this baking modes. The temperature profile in the hybrid baked breads (IMCB1 and IMCB2) demonstrated rapid initial heating across top, centre, and bottom zones, with no further temperature increase after 4 minutes. A slight temperature decrease at 5 minutes indicates a transition from industrial microwave to conventional oven in both IMCB's baking breads (Fig 2c and 2d). Hybrid approach showed balanced heat distribution, minimizing temperature variation across top, centre, and bottom near 100 °C, reflecting improved thermal uniformity in IMCB1 and IMCB2 compared to CB baked breads. Temperature profiles in all hybrid breads demonstrated that combining microwave and conventional oven ensures rapid, controlled heat penetration, minimizes surface drying and localized overheating, and enhanced heating uniformity across different zones [8]. CB breads, subjected to longer baking durations, exhibited the highest hardness values compared to IM and hybrid-baked samples. Furthermore, IMCB2 demonstrated greater hardness than IMCB1 on days 1, 5, and 8 of storage, which can be attributed to its five-minute longer baking with conventional oven



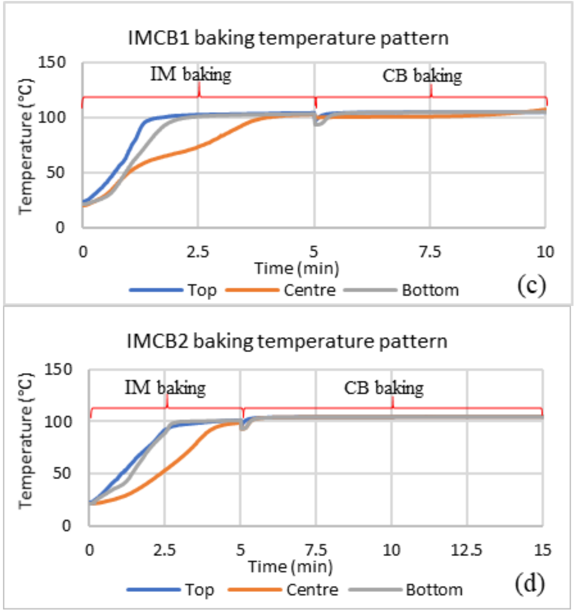


Fig. 2. Temperature variation in a) CB, b) IM, c) IMCB1 and d) IMCB2.

3.3 Humidity measurements

Fig 3 (a,b,c,d) shows moisture distribution in breads baked with different baking modes. In general, there was no significant difference between moisture variation of top, centre and bottom in all baked bread. But the top of all breads still dried faster compare to centre and bottom due to surface exposure of microwave radiation and hot air in conventional oven. As can be seen in all Fig.3, the centre in all baked breads retained more moisture because evaporation occurs first at the outer layers, creating a moisture gradient from the centre outward. This means moisture must migrate from the centre to the crust, delaying moisture loss in the middle of the bread [9]. Also, according to Fig 2 (all), the temperature in all baked bread is highest at the top and lowest at the centre and as a result, water in the centre takes longer to reach boiling point, leading to slower moisture loss in centre [10]. Bottom zone in all breads show more moisture loss than centre due to its direct exposure to baking tray.

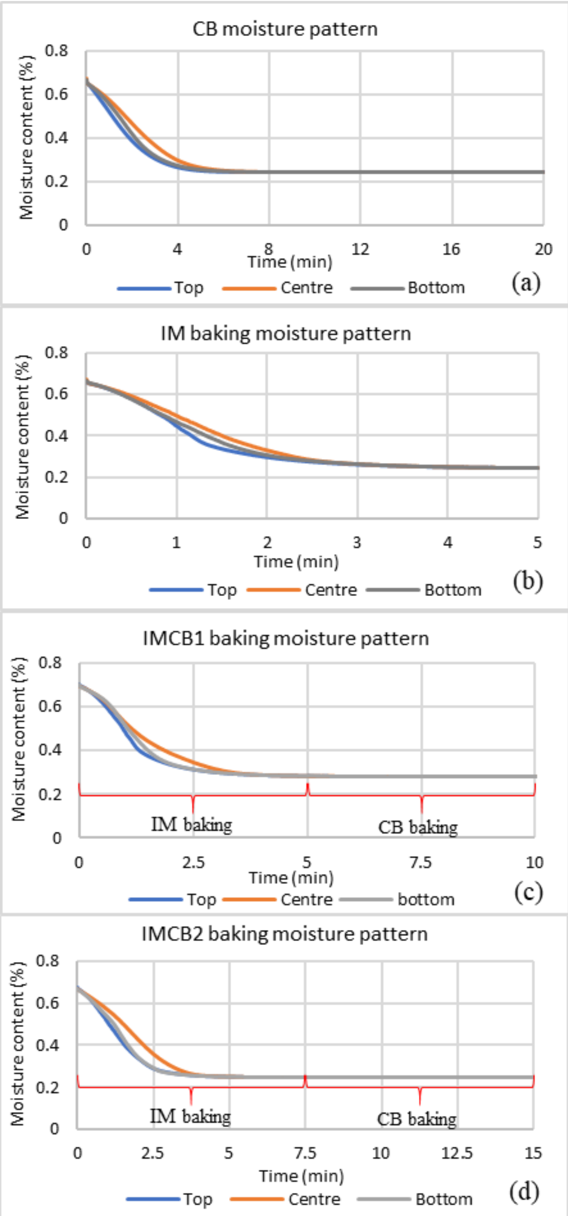


Fig. 3. Moisture variation in a) CB, b) IM, c) IMCB1 and d) IMCB2.

Table 1 presents the energy consumption, cost and GHG emissions of different baking modes. It can be seen that IM baking resulted in the lowest energy consumption, greenhouse gas emissions, and cost, making it the most efficient and sustainable method. In contrast, conventional baking required significantly more energy due to indirect heat transfer and the need to preheat oven components. The hybrid methods offered improved energy efficiency through direct internal heating, reduced baking times, and lower environmental impact [11].

Table 1. Energy consumption, cost and carbon emission of different baking technologies.

Samples	Energy consumption (kWh)	Total cost (£)	GHG emission (Kg of CO_2)
CB	0.453[a]	0.1532[a]	0.086[a]
IM	0.035[g]	0.0054[g]	0.006[g]
$IMCB_1$	0.118[f]	0.0401[f]	0.022[f]
$IMCB_2$	0.148[e]	0.0503[e]	0.028[e]

4 Conclusions

This study demonstrated that baking mode significantly influences the hardness, temperature distribution, and moisture retention of bread during baking and storage. IM baking yielded the softest texture due to its uniform heat distribution, while CB baking resulted in the highest hardness values among all bread samples. Hybrid baking methods ($IMCB_1$ and $IMCB_2$) effectively combined the advantages of both approaches, promoting uniform temperature profiles and balanced moisture distribution. Also, results showed that IM baking is a sustainable baking technology that improve energy efficiency while reducing GHG emission. These findings highlight the potential of microwave-assisted hybrid baking to improve bread quality by enhancing texture, reducing baking time, and minimizing uneven moisture and heat distribution across the loaf while reducing environmental impact.

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